NECESSE
THE NORWEGIAN DEFENCE UNIVERSITY COLLEGE
THE ROYAL NORWEGIAN NAVAL ACADEMY
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ErgoShip 2021 – Maritime artikler

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Innhold

Forord

Lesere,
som stolt sjef for Forsvarets Høyskole-Sjøkrigsskolen er det alltid gledelig å skrive forord i NECESSE.

Kraften bak NECESSE kommer av det alltid tette forholdet mellom FHS Sjøkrigsskolen og Sjøforsvarets navigasjonskompetansesenter.

Skriftserien er meget viktig. Den løfter frem reflek- sjoner og erfaringer rundt det å kunne operere på havet under tidvis meget krevende forhold.

Det er en fare ved det å synse på sviktende grunnlag om kompetanseområder man selv ikke har erfaring fra. Skriftserien NECESSE er et verktøy som reduserer en slik fare.

Denne utgaven fremmer viktige synergier mellom det sivile- og det militære maritime samfunn; det er bare å glede seg til interessant lesning.

Ergoship-konferansene gir en basis for å løfte frem sentrale problemstillinger; så bra at redaksjonen ser slike muligheter.

Tusen takk for innsatsen til hovedredaktør orlogskaptein/ førstekompetent Stein Hatlem Forsdahl, og til redaktørene/ orlogskapteinene Henning Sulen (MSc) og Frode Voll Mjelde (MSc).

Tusen takk til dere som publiserer i denne utgivelse. Dere klarer dette ved siden av en allerede hektisk hverdag:

BZ - Well Done!

Med hilsen,

Bård Eriksen
Kommandør
Sjef FHS Sjøkrigsskolen

Welcome to the special issue dedicated to the conference Ergoship 2021

Welcome to the special issue dedicated to the conference Ergoship 2021! The editorial committee are proud to present a selection of papers from Ergoship 2021 and a few invited papers within the topic of maritime Human Factors.

The first Ergoship was held in Gothenburg in 2011 to create a meeting place for researchers in maritime Human Factors. The conference has lived on and was held in Australia 2016, in Haugesund 2019 and in South Korea 2021. We wish we could all have met in person, but this time it was not to be. Nevertheless, we look forward to sharing these papers with you and hope we can drive this field forward together. Enjoy the papers from a small but passionate group of contributors. The authors and the audience make this recurring conference special.

Margareta Lützhöft
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Hvor robust er losenes navigasjonsutstyr?

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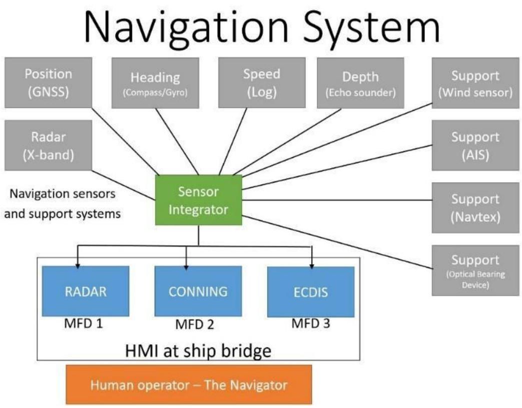
Abstrakt – I det maritime domenet, og på skipsbroen, er det en økende avhengighet av elektronisk navigasjon, spesielt automatisk posisjonering fra GNSS. Kystverket lostjenesten skal besørge sikker seilas for lospliktige fartøy i norske farvann, og den losfaglige kompetansen beror både på tradisjonelle og elektroniske hjelpemidler. Økt bruk av elektroniske hjelpemidler for posisjonering introduserer også en potensiell økt sårbarhet. Artikkelen analyserer resultatene av test av sårbarhet på losenes utstyr. Grunnlaget for analysen var en test initiert av Statens vegvesen der Forsvarets Forskningsinstitutt (FFI) gjennomførte jamming og spoofing av sensorene som losene bærer med seg om bord. Dette er utstyr som kommer i tillegg til skipets utstyr. Kystverket lostjenesten benytter seg av personlig standardutstyr (ADQ2+) og høyytelsessensorer (XR2) levert av AD Navigation. Utstyret ble utsatt for jamming og narring og det ble oppdaget at sensorer som kun inneholder GPS L1 er mye mer sårbart enn enheten som inneholder flere GNSS bånd (XR2). XR2 opererer på et bredere frekvensspektrum og har dermed mer motstandskraft og holder lengre i et miljø med interferens.
Det ble belyst at nøyaktig posisjonsbestemmelse ved RTK og prosessering av retning (heading) er mer sårbart enn å prosessere en pseudo-range posisjonsløsning. Det er også forskjell på hvorledes de forskjellige kartsystemene viser verdier og alarmer som er forårsaket av interferens. Ingen alarmer gir et varsel om mulig interferens.
Testen ga et godt grunnlag for innovasjonsprosjektet som skal utvikle et mer robust system for Kystverkets loser.

Søkeord
GNSS sårbarhet, Jamming, Spoofing, Narring, Los, Navigasjonssensorer, Kystverket, Innovasjon, Navigasjonsteknologi.

Bakgrunn

Maritim navigasjon har gjennomgått et paradigmeskifte de siste tiårene med innføring av elektronisk navigasjon (Norris, 2010). Elektronisk navigasjon er alle hjelpemidler knyttet til navigasjon som går på strøm, og det mest kjente er av mange elektroniske kartsystem. Electronic Chart Display and Information System (ECDIS) har blitt godkjent av IMO for papirløs navigasjon. På moderne skip er det i dag avanserte integrerte navigasjonssystemer (Figur 1) som kobler sammen flere sensorer som til slutt presenteres på et display, gjerne kjent som Multi Function Display (MFD). Innføringen av papirløs navigasjon har utvilsomt bidratt til økt sjøsikkerhet (Weintrit, 2009), samtidig som det har ført til en ny type ulykker. Maritime Investigation Accident Board (MAIB) omtaler dette som ECDIS-assisterte ulykker (MAIB, 2014), og er i stor grad relatert til manglende systemforståelse og høy tillit til posisjonen som er presentert av det valgte elektroniske posisjoneringssystemet. I det maritime er det hovedsakelig posisjon levert av NAVSTAR GPS (IMO, 2007), men det er også mottagere som benytter multikonstellasjons Global Navigation Satellite Systems (GNSS) sammen med støtte fra differensiell satellittnavigasjon som; Differential GPS (DGPS), Satellite-based Augmentation Systems (SBAS) og Ground Based Augmentation System (GBAS) (Hofmann-Wellenhof, 2008).

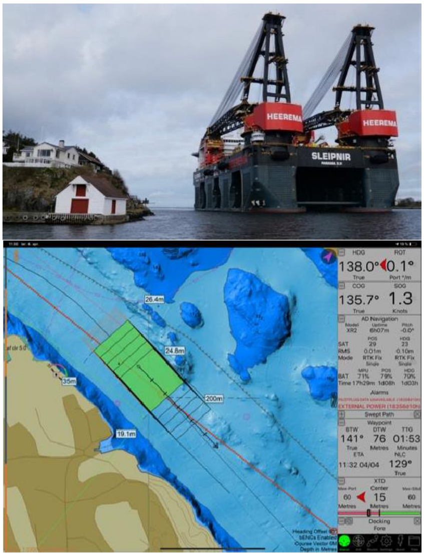


Figur 1: Prinsippskisse integrert navigasjonssystem

Sårbarheten knyttet til GNSS ble først anerkjent i Volpe-rapporten fra 2001 (Volpe, 2001), som konkluderer med at samfunnet er generelt sett avhengig av globale navigasjonssatellittsystem (GNSS). Det er i ettertid kommet en rekke rapporter som påpeker de samme utfordringene, blant annet fra The Royal Academy of Engineering (RaENG,

2011) og Norsk Romsenter (NRS, 2013). I det maritime domenet er det de siste årene blitt et økt fokus på sårbarheten til posisjonsbestemmelse fra GNSS, blant annet gjennom rapporter om både narring og jamming av posisjon til skip fra Svartehavet, Middelhavet, Østersjøen og andre plasser. Et forskningsprosjekt utført av Texas University viste at de endret kurs til et cruiseskip i Middelhavet (Psiaki & Humphreys, 2016).

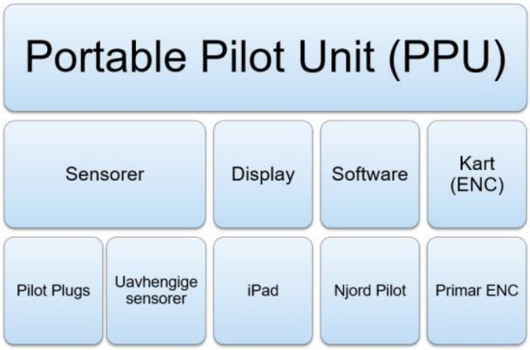
Kystverket lostjenesten bidrar til å trygge ferdselen på sjøen og verne om miljøet ved å tilføre fartøyets mannskap nødvendig farvannskunnskap. Losen er kapteinens nautiske veileder i navigering og manøvrering. Selv om losen i dag har tilgang til stadig mer avanserte digitale verktøy, er det fremdeles kompetanse rundt farled og kyst, værforhold og seilingsrutiner som er hovedproduktet som tilbys fra losen og Kystverket. Lostjenesten utfører omlag 40 000 oppdrag per år (Kystdatahuset.no), og har 7 losoldermannskap og 25 losstasjoner i Norge, fra Halden til Kirkenes. Oppdragene varierer i kompleksitet, fra korte losinger til havn og til mer komplekse operasjoner med små marginer (uvanlige losoppdrag).



Bilde 1: Eksempel på spesialoppdrag er kranfartøyet Sleipnir sitt anløp i Haugesund

På normale eller rutineoppdrag, er losen tjent med nøyaktigheten en PPU gir. Noen ganger er marginene små og losen må dimensjonere utstyret deretter. Dette kalles uvanlige losoppdrag eller spesialoppdrag (Bilde 1). Disse jobbene krever planlegging og koordinering i form av møtevirksomhet i forkant. Dette for å fastsette maksimum grense for vær, vind og sikt, eller minimum klarering til bunn eller land.

Samtidig ser Kystverket lostjenesten en økende etterspørsel etter at losene bidrar med veiledning og støtte også innenfor elektronisk navigasjon. Dette har ført til at losen har med seg Portable Pilot Unit (PPU) på losoppdrag (Figur 2). Portable Pilot Unit er et samlebegrep for utstyret som losen har med seg ombord, og består av tre hovedkomponenter; Sensor, display og programvare. Denne artikkelen vil også sette søkelys på PPU Sensorer for å se om det kan være nyttig i forbindelse med utvikling av neste generasjons høyytelse PPU sensor for Kystverket lostjenesten.



Figur 2:Oppbygning av losens støttesystem, Portable Pilot Unit (PPU)

Innledning

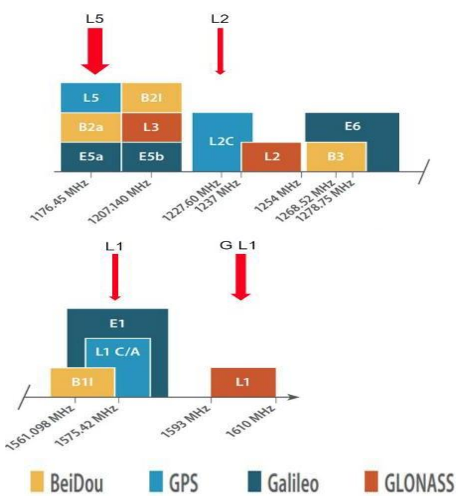
Lostjenesten skal gjennom et innovasjonspartnerskap utvikle fremtidens støtteverktøy for lostjenesten (IA, 2020) i perioden 2020-2023, og deltok i september 2021 på en jammetest der dagens utstyr ble utsatt for signalinterferens.
Målet med testen var å utforske hvor sårbart eksisterende navigasjonssensorer (PPU sensor) er, samt identifisere hvordan dette påvirker navigasjonssystem (PPU software - Njord Pilot og SeaIQ) som er mest brukt av losene.
I tillegg var målsetningen å undersøke om noe av denne lærdommen kunne brukes som innspill til innovasjonspartnerskapet, der neste generasjon støttesystem for lostjenesten skal utvikles.

Gjennomføring

Testene var ledet av Statens Vegvesen der hovedfokus var sensorer i biler. Sensorene som losene bruker, ble derfor satt på en bil (se bilde 2) for å simulere hvordan de monteres om bord på et lospliktig fartøy.

Bilde 2: Losens sensorer plassert på bil

FFI var ansvarlig for sender utstyr og hadde mulighet å jamme på frekvensene beskrevet i Figur 3. Tabell 1 viser at XR 2 bruker flere bånd enn de som var mulig å jamme på. Det er verdt å merke seg at noen av frekvensene i de bånd som ikke ble jammet på er lik, eller ligger nær de bånd som det ble jammet på, for eksempel GLO L2 som er nær GPS L2 og GPS L2C som er samme området som GPS L2. Båndene kan imidlertid ha forskjellig struktur som gjør at de kan påvirkes forskjellig.



Figur 3: GNSS frekvenser og bånd. Rød pil er bånd som kunne jammes. (Kilde FFI)

Frekvens bånd	Senterfrekvens MHz	PRN rate MHz	ADQ2+ 1561-1610	CatRot 1561-1610	XR2 1207-1256 1561-1610	Garmin 1561-1610
Mulige Jamme freq						
GPS L1	**1575.42**	**1**	X	X	X	X
GLO L1	**1601.72**	**5**			X	
GPS L2	**1227.6**	**1**			X	
GPS L5	**1176.45**	**10**			X	
Ikke jammet bånd som XR 2 bruker						
GLO L2	**1598-1609**				X	
GPS L2C	**1227.6**	Samme freq som GPS L2			X	
Galileo E1	**1575.42**	Samme freq som GPS L1			X	
Galileo E5b	**1207.14**				X	
Beidou B1l	**1561.098**	Nært GPS Ll			X	
Beidou B2l	**1207.14**	Nært GPS L5			X	

Tabell 1: Frekvenser det var mulig å jamme på sammen med oversikt over hvilke bånd sensorene bruker (GLO=Glonass)

I de fleste moderne jammere er det mulig å generere forskjellige jamme signaler og bølgeformer. Forskjellen mellom jammersignal og jammerbølgeform er at bølgeform består av flere jammersignaler som representerer en sekvens av jamme signal på ønsket frekvens.

Jammetyper som ble brukt var Continous Wave (CW) og Pseudorandom Noise (PRN). CW betyr at jammesignalet svinger med en fast frekvens, mens PRN er jamming med et signal som har omtrent samme form (i frekvensspekteret) som de ekte signalene fra satellittene. PRN kalles også bredbåndsjamming.

Alle sensorer (Bilde 3), 5 i alt (1 håndholdt Garmin, bilens system og 3 iPader med tilkoblede PPU sensorer) var satt opp på alle testene. Garmin mottaker ble brukt da den har et bilde med skyplott (bilde over satellitter på himmelen) og signal støyforhold som er nyttig. Bilens mottaker ble også brukt som referanse da den hadde visning av antall satellitter.

Bilde 3: 3x iPad med kartsystem, Garmin og bilens kartsystem

Det ble lagt opp til flere forsøk med forskjellige parameter som ga et godt grunnlag for en bred test av losens sensorer.

Losens sensorer og kartprogram

Til vanlige losoppdrag benytter losene ADQ-2+ PPU (Portable Pilot Unit Sensor - PPU Sensor), levert av AD Navigation. Denne kobles til skipets AIS med en pilotplug (ledning). ADQ2+ videresender skipets posisjon (fra skipets GPS), antenne offset, fysiske dimensjoner og AIS mål, via Wifi. I tillegg har ADQ2+ en innebygget GPS og en ROT (Rate of turn) sensor. I praksis benyttes kun ROT fra ADQ2+ og resten er fra skipets AIS via pilotplug.

Bilde 5: ADQ2+ og de tre enhetene i XR2

Til uvanlige losoppdrag (spesialoppdrag) hvor det er større krav til nøyaktighet i posisjon, benyttes XR2. Denne er også levert av AD Navigation og består av tre PPU sensorenheter.

XR2 systemet er et uavhengig og vesentlig mer nøyaktig enn ADQ2+. Til posisjon benyttes en multifrekvens mottaker med alle konstellasjoner (GPS/Glonass/BeiDou/Galileo). De tre boksene kommuniserer seg imellom via UHF. Master Processing Unit (MPU) (Bilde 4) boksen prosesserer all data og videresender denne via Wifi.

XR2 bruker to av enhetene til å frembringe heading og har RTK kapasitet for bedre nøyaktighet (se kapittel; Multikonstellasjon og multifrekvensmottaker XR2).

Bilde 4: Kartprogram Njord Pilot

Kartprogrammet som losene benytter er Njord Pilot (Bilde 4) levert av SevenCs.
Dette programmet kjøres på iPad (iOS), som er losenes arbeidsverktøy. Under testene ble også programmet SeaIQ benyttet, da det er utbredt internasjonalt samt har mer informasjon og verdier som er nyttig under jamming og spoofing. For eksempel var funksjonen; *Sammenligne Ext NMEA med innebygget GPS* nyttig under spoofing angrep, for å enkelt kunne sammenstille visuelt posisjonene gitt av to ulike posisjonskilder.

Funn

Innledning

Alle testene ble styrt av FFI som genererte jamming eller spoofing enten på alle frekvensene samtidig eller en frekvens etter den andre. Testen ble enten gjort med maksimal utgangseffekt eller stegvis opp eller ned. Jammer var alltid stasjonær. Ved kun en av testene var sensorene i bevegelse, ellers stasjonære. Logging ble gjort ved å notere fortløpende. Elektronisk logging ble gjort med screen grabber og logging av NMEA data på PC via loggeprogrammet Tera Term. Det var direkte samband med FFI som opplyste tid og hva som ble initiert. Observasjon av sensorene ble gjort av to personer.

Test 1; CW jamming, økende frekvensbånd

I test 1 ble det jammet på CW i sekvens GPS L1 - GLO L1 - GPS L2 - GPS L5, deretter motsatt rekkefølge. Avstanden til jammer var 17 meter og utsendt effekt var 0,1 watt som var maksimum jammeeffekt. Sensorer og jammer var stasjonær.

Allerede ved jamming av GPS L1 var alle sensorene som kun baserer seg på GPS L1 slått ut. XR 2 som har flere bånd og frekvenser opprettholdt posisjonsbestemmelse (Tabell 2).

	GPS L1	GLO L1	GPS L2	GPS L5	Garmin	Catrot	XR2	ADQ2+
09:53	X				Ikke fix	Ikke fix	fix	Ikke fix
09:57	X	X			Ikke fix	Ikke fix	fix	Ikke fix
10:00	X	X	X		Ikke fix	Ikke fix	fix	Ikke fix
10:02	X	X	X	X	Ikke fix	Ikke fix	fix	Ikke fix

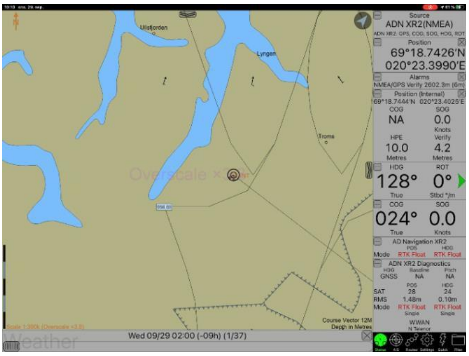
Tabell 2:Resultat jamming ved å legge til nye bånd, men start på GPS L1(X betyr at bånd blir jammet)

Noen indikasjoner på problemer også på XR 2 kom også når alle 4 bånd var jammet, men den holdt posisjonsbestemmelse.

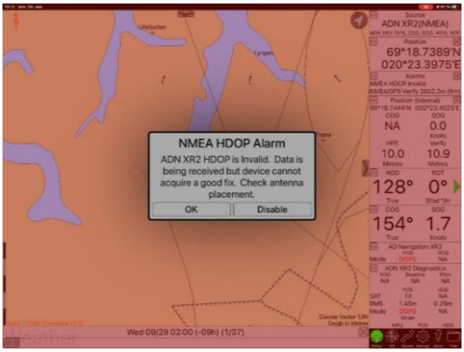
Når alle bånd var jammet begynte del to av testen der båndene ble jammet i motsatt rekkefølge (start med GPS L5). Resultatet ble da litt annerledes da XR2 fikk problemer med RTK allerede ved jamming av GPS L2 og RTK fikk problemer ved jamming av GLO L1 (Tabell 3).

	GPS L1	GLO L1	GPS L2	GPS L5	Garmin	Catrot	XR2	ADQ2+
10:07				X	fix	fix	fix	fix
10:09			X	X	fix	fix	fix	fix
10:10		X	X	X	fix	fix	fix RTK probl	fix
10:12	X	X	X	X	Ikke fix	Ikke fix	fix, RTK probl, få sat, alarmer	Ikke fix

Tabell 3:Resultat jamming ved å legge til nye bånd, start på GPS L5



Bilde 6: Skjemdump SeaIQ. Tid 10:10 Ustabil og i mode RTK Float



Bilde 7: Skjermdump SeaIQ. Tid 1012, viser RTK float, ikke Fix, Heading Ok på grunn av backup

Dette kan indikere at XR2 bruker GPS L2 eller GLO L1 for å få RTK løsning. Da GPS L1 også forvant mistet alle de andre fix (posisjon) men XR2 slet betydelig mer enn ved forrige test, noe den alarmerte om.

Etter dette ble samme test gjennomført, men jammesignalet var PNR, bredbånd (se kapittel; Gjennomføring på side 3). Den samme utviklingen skjedde her, men XR2 mistet helt posisjon ved jamming av det tredje og fjerde båndet uansett hva som startet først.

Testen viste dermed at PNR jamming gikk hardere utover multikonstellasjons- og multifrekvens-mottaker XR 2 enn CW jamming.

Test 2; PNR Jamming, Gradvis økning av effekt

Test 2 startet med lav effekt; 85dB demping med 5 dB steg. Signalet var PRN og det var jamming på alle 4 bånd. Denne testen ville gi indikasjoner på hvordan systemene påvirkes av svak jamming og hvilke indikasjoner som kommer først.

Oppsettet på sensorer og kartprogram var som tidligere. Sensorer og jammer var stasjonære.

Dempning	Tid	GPS L1	GLO L1	GPS L2	GPS L5	Garmin	Catrot	XR2	ADQ2+
85 db demp	11:13:07	X	X	X	X	fix	fix	fix	fix
80 db demp	11:14:35	X	X	X	X	fix	fix	fix	fix
75 db demp	11:17:29	X	X	X	X	fix	fix	fix	fix
70 db demp	11:17:29	X	X	X	X	fix	fix	fix	fix
65 db demp	11:21:11	X	X	X	X	fix	fix, HDOP 1,5	fix	fix
60 db demp	11:24:41	X	X	X	X	fix	fix, HDOP 1,5	fix HDOP 0,6	fix
55 db demp	11:25:06	X	X	X	X	fix	fix, HDOP 1,6	fix HDOP 0,6	fix
50 db demp	11:26:22	X	X	X	X	fix	fix, HDOP 1,1	fix HDOP 0,6	fix
45 db demp	11:25:56	X	X	X	X	fix	fix, HDOP 1,2	dårlig fix RTK probl	fix
40 db demp	11:32:02	X	X	X	X	svak fix	fix drop i SNR	fix	fix
35 db demp	11:33:38	X	X	X	X	svak fix	fix drop i SNR	fix	fix
30 db demp	11:27:11	X	X	X	X	Ikke fix	fix drop i SNR HDOP 1,6	fix HDOP 0,6	fix
20 db demp	11:41:00	X	X	X	X	Ikke fix	Ikke fix	fix HDOP 0,7	fix, svak
10 db demp	11:46:00	X	X	X	X	Ikke fix	Ikke fix	fix HDOP 2,1	Ikke fix
5 db demp	11:49:00	X	X	X	X	Ikke fix	Ikke fix	pos, Heading er borte,Hopper i pos	Ikke fix
0 db demp	11:57:00	X	X	X	X	Ikke fix	Ikke fix	Ikke fix	Ikke fix

Tabell 4:Resultat PNR Jamming med gradvis reduksjon i dempning

Tabell 4 viser at det allerede ved 65dB dempning kom indikasjoner på en høyere HDOP verdi på Catrot. XR2 som har mange flere satellitter å velge mellom har derimot ikke noe problem med HDOP. Garmin og ADQ2+ hadde muligens høyere HDOP verdi, men dette vises ikke på kartprogrammet. Ved 45 dB demping ble det noe problem med RTK og noe dårligere fix. Dette kom seg imidlertid etter noen sekunder. Ved 40dB demping som tilsvarer 10 mikrowatt utsendt effekt viste også Catrot og Garmin en nedgang i signal-støyforhold fra ca 40dB til ca 25dB som er på grensen til å klare å frembringe posisjon. Ved dempning 30 til 10dB (10 db demping =10 milliwatt effekt) mistet som forventet GPS L1 mottakerne fix. Etter det forsvant heading fra XR2, posisjonen ble ustabil og til slutt var den også helt jammet ut tilsvarende de andre testene.

Også her håndterte XR2 interferens best. Den får først problemer med RTK så litt høyere HDOP, mister heading og posisjon til slutt.

Test 3; Spoofing (narring)

Test 3 gikk ut på å narre tid og posisjon på GPS L1. Det var først 5 min jamming etterfulgt av Spoofing angrep på GPS L1. Både tiden på posisjon ble forfalsket og sendt til mottakerne. Plassering var det samme som i forrige test.

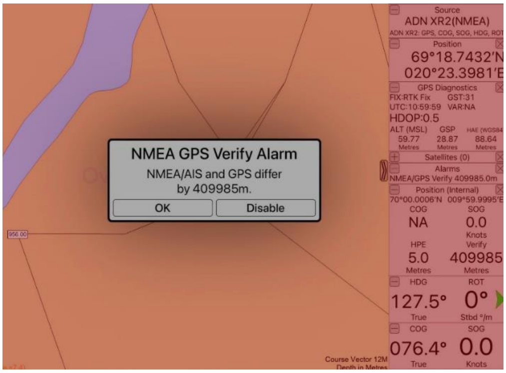
Etter 5 min jamming var posisjon borte fra alle enheter deretter ble spoofing satt i gang på GPS L1

Type PPU	CatRot	ADQ2+	XR2
Spoofet	Ja	Ja	Nei
iPad med SIM kort	Ja	Ja	Nei
Intern iPad GPS spoofet	Nei	Nei	Ja

Tabell 5; Viser om enhetene ble spoofet eller ikke

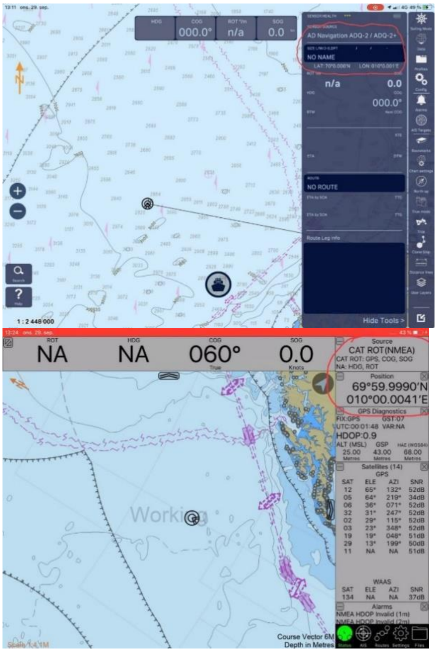
I stort ble alle som er avhengig av GPS L1 spoofet (Tabell 5). XR2 ble ikke spoofet men viste alarm om at den interne GPSen i iPaden var vesentlig forskjellig fra XR2 sensorene (Bilde 6).

Det visste seg svært nyttig å få en alarm som visste avvik mellom intern (innebygget GPS iPad) og ekstern PPU (Bilde 6).



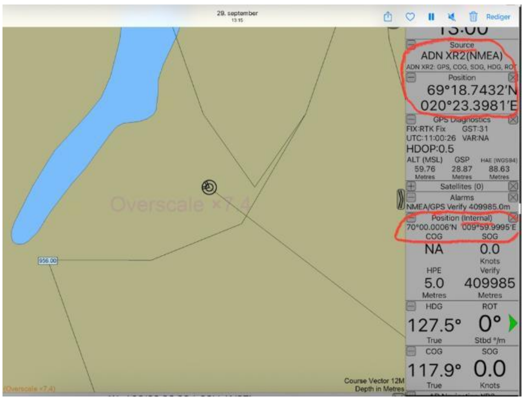
Bilde 6: Skjermdump SeaIQ. Alarm om forskjell på intern GPS og XR2 sensorer

Alarmen var nyttig, men det burde også være en alarm om at pos på GPS L1 ikke stemte.
ADQ2+ og CatRot var tilkoblet iPad med SIM kort installert. Her ble begge PPU'ene spoofet, mens den innebygde iPad GNSS sensoren beholdt riktig posisjon (Bilde 7).



Bilde 9. Skjermdump Njord Pilot og SeaIQ. ADQ2+og Catrot spoofet ut i havet (40mil unna)

XR2 er en multimottaker og var tilkoblet en iPad uten SIM kort installert. Her ble den innebygde iPad GPS spoofet, mens XR2 beholdt riktig posisjon (Bilde 7).



Bilde 7: Skjermdump SeaIQ. XR2 beholdt riktig posisjon under spoofing test, mens den interne GPS ble spoofet

Test 4, Jamming, test av skjerming med metallring (kakeboks)

Effektrampetest - starte med lav effekt og øke stegvis oppover til alt er slått ut

Testen ble utført på alle bånd. Oppsett som tidligere, men det ble kjøpt inn en Kakeform (26cm i diameter) som skulle brukes som en skjerm mot jammeren (Bilde 8).

Bilde 8:Skjerming av sensor

Selve testen ble utført med to ADQ-2+ PPU (hvor den ene ble forsøkt skjermet, Bilde 8) samt en XR2. Under testen ble kartprogrammet SEAiq og Njord Pilot benyttet. Antennene (PPU) ble plassert på biltak, ca 7m fra jamming antenne. Ved å sammenligne de to identiske ADQ2+ ville det bli mulig å se om det ble en forbedring på den som var skjermet.

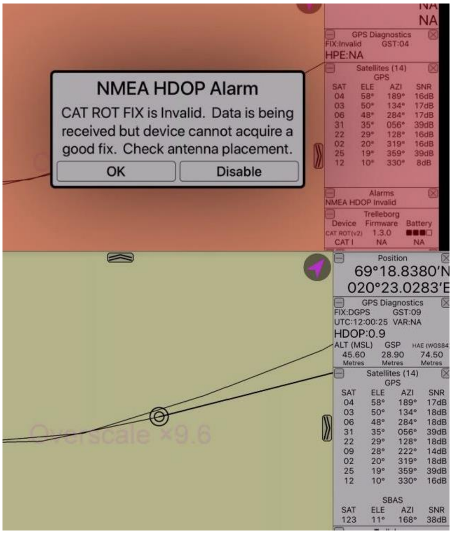
Fra starten, uten jamming tok den skjermede inn 1-2 færre satellitter, noe som skyldes selve kakeboksens høyde (skjermingseffekt). Ved 40dB dempning fikk begge problemer med HDOP men verdiene var like. Til sammenligning hadde XR2 nå 24 satellitter tilgjengelig, en nedgang fra 32 i starten. Ved 28dB demping ble det forskjell på de to. Den skjermede mistet fix mens den uten skjerming klarte seg akkurat. Ved 22dB demping mister XR 2 heading og RTK samt at viser at den har ca 16 tilgjengelige satellitter.
Testen viste at den skjermede sensoren ga dårlige geometri og mistet signalet før den som ikke var skjermet.

Test 5, Jammer med PRN (alle bånd) signal stasjonær, bil passerer.

I denne øvelsen kjørte bilen forbi en jammer i henholdsvis 90 og 50 km/t. Jamming på alle bånd og 0,1 watt effekt. PPU ADQ2+, CatRot og XR2 ble benyttet og festet med magnet til bilens tak.

Jammer var plassert nær veien slik at den ville ha effekt i hele veibanen et stykke før passering og etter passering. PPU ADQ2+, CatRot og XR2 ble benyttet og festet med magnet til bilens tak. Ved passering av jammer falt både ADQ2+ og CatRot ut. XR2 beholdt posisjon, men gjorde et utfall mot jammer.

Det ble kjørt begge veier (på retur var farten redusert til 50 km/t) og observerte det samme.



Bilde 10:Skjermdump SeaIQ. Passerer jammer i fart, få sekunder seinere alarm.

Analyse

Innledning

Analysen baserer seg på observerte data sammenstilt med de elektronisk loggede data samt en detaljert oversikt over utført jamming og spoofing gitt av FFI.

Analysen fokuserer på målene som var å finne sårbarheten hos losenes navigasjonssystem og på de erfaringer som vil gi viktige innspill i innovasjonsprosjektet.

Sensorer med GPS L1 alene

PPU ADQ2+, CatRot og Garmin har kun mulighet til å motta signaler fra GPS L1. GPS L1 er det åpne og mest brukte signalet til GPS. International Committee on Global Navigation Satellite Systems (ICG) er kommet til enighet i å ha en felles frekvens som var kompatibel med alle GNSS systemer. En av begrunnelse beskrives de slik i ICG vision statement (ICG, 2021).

> *«The International Committee on Global Navigation Satellite Systems (ICG) strives to encourage and facilitate compatibility, interoperability and transparency between all the satellite navigation systems, to promote and protect the use of their open service applications and thereby benefit the global community.»*

Alle 4 systemene har derfor en kompatibel frekvens nær eller lik GPS L1 som har sine fordeler, men på den annen side også gjør de mer sårbare.

Nettopp denne sårbarheten ble synlig på testene som ble avholdt. Så snart GPS L1 ble jammet var ADQ2+, CatRot og Garmin ikke i stand til å gi posisjon. Om de hadde vært multibånd mottakere hadde det sannsynligvis ikke hjulpet stort, men dette ble ikke avdekket under disse testene.

Testene viser at når Signal-Støyforholdet (SNR) kommer under ca 20dB vil mottakene slite med å levere posisjon. Det viste seg at både økt HDOP verdi og lav SNR kommer omtrent samtidig. Dette viser at alarmer som enten viser høy HDOP verdi eller reduksjon i SNR begge kan være indikasjoner på interferens. Forutsetning er imidlertid at høy HDOP verdi ikke skyldes fysisk skjerming av satellitter. På en multiband mottaker på L1 båndet vil det være flere satellitter synlig de aller fleste plasser. En høy HDOP verdi på en slik mottaker vil dermed være en enda sterkere indikasjon på interferens.

En fellesnevner for alle testene var at disse mottakerne klarte seg når andre bånd ble jammet, men ble raskt slått ut når GPS L1 ble jammet.

HDOP (horizontal dilution of precision)
HDOP Verdi er en funksjon som viser om nøyaktigheten blir redusert av ikke-optimal geometri på det mottatte satellittene. Ved flere enn 4 satellitter tilgjengelig kan mottakeren velge de som gir best geometri og dermed redusere unøyaktigheten som følge av dårlig geometri. Lav HDOP er bedre og HDOP=1 er ideelt (Kjerstad, 1997; Kystverket, 2021)

DOP Value	Rating	Description
1	Ideal	Highest possible confidence level to be used for applications demanding the highest possible precision at all times.
1-2	Excellent	At this confidence level, positional measurements are considered accurate enough to meet all but the most sensitive applications.

Bilde 11: beskrivelse av HDOP verdi (Kilde: marxact.com/article/111)

Mottakerne brukt under testene har alle mange kanaler og kan velge de beste satellittene, noen av mottakerne flere enn andre. På mottakerne med kun GPS L1 er det færre muligheter enn ved XR 2, men en felles erfaring var at redusert HDOP verdi er en av de første indikasjonene på at det er interferens til stede. XR2 var som forventet mindre påvirket enn for eksempel ADQ2+. I test 2 viste det seg at ved 20dB demping hadde XR2 en HDOP på 0,6 og Catrot 1,6. Når Catrot og ADQ2+ hadde mistet fix hadde XR2 fortsatt kun en redusert nøyaktighet på grunn av geometri med HDOP på 2,1. Dette viste at det var viktig med en god presentasjon av HDOP til brukerne av kartsystemer.

Multikonstellasjon og multifrekvensmottaker XR2
XR2 mottar både på flere bånd og flere frekvenser. Dette er gjort nettopp for å gjøre mottakeren mer robust. I tillegg består XR2 av 3 poder som dermed gir mulighet til å kalkulere en nøyaktigere posisjon ved å utnytte fasemåling (RTK) (Kjerstad, 1997; Kystverket, 2021). Heading poden blir da Rover og posisjons poden Base. Kalkulering av posisjon ved fasemåling er mye mer krevende og sårbart særlig når referanse korreksjonen også er påvirket av interferens. Det er dermed forventet at RTK skal falle ut tidligere enn posisjonsbestemmelse ved vanlig Pseudo Range målinger. Heading beregning er også avhengig av fasemåling og vil også være mer sårbart og er også forventet å falle ut tidligere. Andre fordeler som for eksempel «fast aqusition» blir ikke analysert her (Nesreen, 2015).

I alle testene var det tydelig at XR2 innfridde forventningene og den var klart den mest robuste sensoren. XR2 viste at den hadde ca 32 satellitter tilgjengelig i løpet av testene. Da den mistet posisjon viste den imidlertid ca 12-13 satellitter tilgjengelig noe som burde indikere at dette skulle være godt nok. Analysen har ikke klart å finne ut hva dette skyldes, men en mulig løsning er at visningen av antall satellitter «henger etter» og ikke viser korrekt antall eller at visningen er for «snill». Det vil si at ikke alle satellitter som er synlige kan brukes i posisjonsløsningen. Videre analyser og tester må imidlertid til for å avdekke dette. Analysen av test 1 viser også at XR2 klarte seg bedre når GPS L1 ble jammet til slutt. Den hadde fix selv etter at GPS L1 ble jammet ut til slutt, noe som ikke var tilfelle da GPS L1 ble jammet ut først.

I et jammetilfelle var det forventet at relativ RTK (også benevnt som moving base RTK) først vil bli rammet, og analysen bekrefter dette. Det viste seg også at RTK falt ut når Glonass L2 ble jammet. RTK skal ikke være avhengig av noen spesielle bånd, men i praksis viser det seg at den blir påvirket hvis noen av båndene den bruker er jammet ut. I denne sammenhengen er det interessant å merke seg at den har flere bånd, noen som har samme frekvens som de som ble jammet, noen nært og noen litt lengre unna senterfrekvensen som ble jammet. Testen viste at selv om XR2 har flere bånd og frekvenser, og dermed en bedre mulighet til å opprettholde funksjonen til basen og roveren i interferens på noen av frekvensene, var dette ikke tilfelle og XR2 fikk problemer selv om den hadde flere muligheter. I denne analysen har det ikke vært mulig å få nok innsikt i programarkitekturen eller detaljerte nok tester til å kunne konkludere hvorfor RTK ble degradert når 3 av 10 bånd ble jammet. Det er sannsynlig at det har med kompleksiteten og sårbarheten i beregningen av hvilken bølge mottakerne befinner seg i, kjent som “ambiguity resolution” (Teunissen, Joosten, & Odijk, 1999). En annen faktor kan være at ved reduksjon av antall satellitter, kan base og rover mottakerne få problemer med å se samme satellitt som er en forutsetning for riktig bølgeberegning. Dette er imidlertid ikke mulig å analysere utfra data tilgjengelig fra testen.

Det ble også gjennomført en test som var lik test 1, men jammetypen ble skiftet fra CW til PNR (se avsnitt Gjennomføring). Resultatene var i grovt like, men det var helt tydelig at PNR jamming påvirket mottakerne mer med samme effekt. XR2 mistet fix mens den hadde dårlig fix på CW jamming.

XR2 beregner heading basert på relativ RTK (også kjent som "GPS kompass"), der den 3 dimensjonale vektoren mellom Position pod og Heading pod danner grunnlaget. Heading er mer sårbar fordi både moving base (Position pod) og rover (Heading pod) er eksponert samtidig. Dermed vil GNSS heading antakeligvis falle bort først, og i tillegg gir XR2 heading-backup basert på RoT i 5 minutter. Dette skjer ved at akkumulert RoT legges til siste kjente GNSS heading inntil neste validerte GNSS heading er tilgjengelig. RTK posisjon (referert til Position pod) kan også bli degradert under eksponering. Den er da mindre sårbar så lenge korreksjonene ikke stammer fra en referanse som også er eksponert. Under eksponering er det dog forventet at høyeste nøyaktighet ikke er oppnåelig, og at mottaker rapporterer en RTK float[1], DGPS eller ukorrigert posisjonsløsning. Det kan være mer krevende å slå fast kvaliteten på posisjonen under eksponering.

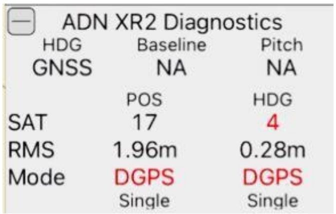
På samme måte som med RTK, viste det seg at heading kalkulering var mer sårbar enn å oppnå pseudo-range posisjon. Grunnen til dette er tilsvarende til at RTK begrenses, samt at heading også er avhengig av fasene i bærebølgene fra to satellitter. Begrunnelsen er dermed mye den samme som for RTK.

Alarmer om mistet heading vil dermed også være en mulig indikasjon på interferens, selv om det også kan være andre årsaker som for eksempel blokkering av satellitter under broer ol. Det er imidlertid viktig å merke seg at heading backup kan gi en forsinkelse i tap av heading på 5 min, men på test 1 og 2 så det ikke ut som om det gikk 5 min til alarmen kom da trinnene i økning av jamming foregikk hvert minutt. For å endelig fastsette årsaken til dette må det utføres flere tester. Ideelt sett bør det komme varsel ved bortfall av GNSS-kompasset selv om backup holder i 5 min.

Kartprograms evne til å opplyse brukeren om interferens

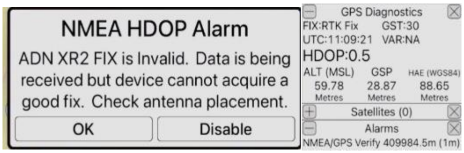
For en operatør av et kartprogram er det viktig å bli varslet hvis noe er galt, særlig hvis feilen potensielt kan påvirke sikkerheten for seilasen. Det ble derfor loggført hvordan programmene varslet om interferens og hvilke nyttige funksjoner som lå i programmene som kan overvåke kvalitet på signalet.

SEAiq og Njord Pilot kom begge opp med alarm når de mister posisjon, heading og RTK. SEAiq er imidlertid vesentlig bedre. Den har et bilde med «Diagnostics» (Bilde 12) som er nyttig.



Bilde 12: Skjermdump SeaIQ. Diagnostic vindu til SEAiq

Ingen av alarmsystem er imidlertid programmert for å varsle om interferens, men for eksempel antenne problemer, som i de fleste tilfeller vil være misvisende (Bilde 13).



Bilde 13: Skjermdump SeaIQ. Nyttige alarmer og info på SEAiq

Under testen så det ut som om sensorene som var tilknyttet Njord Pilot ble mindre påvirket enn de som var tilkoplet SeaIQ. Dette var ikke tilfelle og viser at brukeren trenger god informasjon i de tilfellene sensorene blir påvirket og her har SeaIQ et bedre utgangspunkt enn Njord Pilot.

4G SIM kortets betydning

Spoofing testen viste at den interne GNSS mottakeren i iPaden som hadde SIM kort installert ikke lot seg lure (spoofe) av at feil tid og posisjon ble sendt til iPad. Årsakene til dette er ikke videre analysert i denne artikkelen men det er kjent at iPad fra andre generasjon med simkort benytter «Assisted GNSS» (A-GNSS) (Zandbergen & Barbeau, 2011) og har integrert GNSS modul, som gjør at iPad utnytter navigasjonsdata fra mobildata og ikke fra satellittene (Merry & Bettinger, 2019). Spoofingen innebar en 40 000km og 1 uke offset. Det så ut som om Ipaden mottok tidsinformasjon via A-GNSS som gjorde at den ikke ble lurt på tiden, noe som kan være årsaken til at iPad med sim-kort ikke lot seg spoofe.

[1] I en Float-løsning er algoritmen ikke løst (ennå) og kan ikke produsere en akseptabel FIX-løsning (ennå) Kilde: https://support.marxact.com/article/85-what-is-the-difference-between-rtk-

fix-and-rtk-float.

Det som imidlertid virker klart, er at det kan være nyttig å ha tilgang på 4G (eller tilvarende) som en kilde for verifisering av GNSS data.

Effekt ved bevegelse

Under scenariet der sensorene var i fart og passerte en kilde for interferensen viste det seg enda viktigere at programmene gir en rask og tydelig indikasjon på det sensoren blir utsatt for.
Like før passering av jammer (20-30 sekunder) var det en tydelig reduksjon i signal-støy forhold (SNR) uten at det ble varslet ved alarm. Ved passering var det et tydelig hopp bort fra veien, men på grunn av for lang avstand mellom hvert lagringspunkt fremkommer ikke dette «hoppet» på slepestreken (past track). Hvis ikke operatøren hadde fulgt godt med, ville denne interferensen ikke blitt oppdaget, noe som kan være med på å gi et uriktig situasjonsbilde.
En markert nedgang i signal-støy forhold burde logges og ligge som informasjon til brukeren.

Skjerming av antenne

En måte å hindre multipath (refleksjoner) fra bakken er skjerming. Høy kvalitets antenner bruker høy som for eksempel brukes til landmåling, bruker skjerming som er ringer som sørger for at uønskede signaler ikke når mottakeren. I testene sto jammeantennen i ca. samme høyde som mottakerne på taket og det ble derfor kjøpt inn en skjerm (kakeform) der mottakeren er inne i formen. Resultatet av denne testen var det motsatte av hva som var forventet, den skjermede mottakeren mistet fix før den tilsvarende mottakeren uten skjerming. Analysen her viser at det er vanskelig å konkludere, men det var allerede i starten indikasjoner at den skjermede sensoren hadde 1-2 færre satellitter. Det så med andre ord ut som om skjermen hindret at sensoren kunne ta inn satellitter som hadde lav elevasjon. Skjermen hindre ikke at sensoren ble jammet, noe som også var forventet, men det var marginal forskjell på de to sensorene. Det at den skjermede mistet fix først skyldes sannsynligvis at den hadde 1-2 færre satellitter å spille på.

Konklusjon

Hensikten med testene var å vurdere losenes navigasjonssystem med hensyn på interferens og dens evne å alarmere om interferens. Det var også viktig å få innspill til innovasjonsprosjektet som skal utvikle neste generasjons støttesystem for lostjenesten.

Felles for alle sensorer som kun hadde GPS L1 var at det var svært sårbare for interferensen og mistet fix ved jamming av dette båndet med en effekt på 0,1 watt. Avstand ca 17m.

XR2 som er en multifrekvens og multikonstellasjonsmottaker (mange bånd, GPS, GLONASS, BeiDou med flere) klarte seg som forventet da den hadde alternativer til de jammede bånd. Det viste seg at selv om den hadde bånd som ikke ble jammet mistet den fix likevel da 4 bånd ble jammet. Noe av grunnen til dette er at alle båndene ligge relativt tett, og har sidebånd som går over i hverandre. Kalkulering av RTK og heading bruker fasemåling og er derfor mer sårbar for jamming enn normal posisjonsberegning.

Ved spoofing av tid (1 uke) og posisjon (40 000m) ble alle systemer til slutt lurt, men det er klart mer krevende enn jamming.
Det viste seg også at CW jamming er mindre effektiv enn PRN jamming. Det var indikasjoner på at iPad med SIM kort (A-GNSS) ikke lot seg lure på samme måte som de uten. Dette kan skyldes at den mottar rett tid og «vet» at den er i en basestasjons nedslagsfelt.

Testing av skjerming ga motsatt effekt da satellitter ble skjermet istedenfor jammeren.

De to kartprogrammene, SeaIQ og Njord Pilot hadde forskjellig måte å vise mulig interferens. SeaIQ hadde flere viktige parameter som var lett å hente opp, mens Njord Pilot hadde mindre og «skjulte» dermed viktig informasjon for brukeren. Generelt var alarmer for få og til tider misvisende.

Testene ga den ønskede effekt og målene ble oppnådd både innen måling av robusthet og innspill til innovasjonsprosjektet.

Viktige funn listet opp:

- XR 2 var mest motstandsdyktig på grunn av at den er multikonstellasjonsmottaker og har et bredt frekvensspekter.
- RTK var sårbart når 3 av 10 bånd var jammet og når 4 bånd ble jammet forsvant RTK.
- Heading i XR2 var sårbart da fasemålinger brukes og er lettere å påvirke på grunn av konvergens problematikk.
- XR2 klarte seg også best i narring, men det gjorde også iPad som hadde SIM kort 4G dekning på grunn A-GNSS.
- Det visste seg svært nyttig å få en alarm som visste avvik mellom intern (innebygget GNSS iPad) og ekstern PPU (SeaIQ).
- Skjerming mot jamming hadde med dette oppsettet (kakeboks) motsatt effekt, og førte til færre mottatte signaler eller multipath (flerveis interferens) som forringet sensoren istedenfor å skjerme for jamming.
- Ved svake jammesignaler er HDOP verdien og synkende signal-støyforhold det første som gir indikasjon på interferens.
- PRN jamming er mer effektiv enn CW jamming.
- Alarmer er ikke tilpasser interferens.

Fremtidig forskning:

- Teste RTK mottaker og hva som gjør at den går i float (jobber med å få fix) når den fortsatt har bånd tilgjengelig.
- Hvordan effektivt presentere alarmer ved interferens for å øke operatørens situasjonsbevissthet.
- Teste XR2 mottaker med tanke på hvorfor den ikke klarer å beregne fix med mange satellitter tilgjengelig.
- iPad med A-GNSS virkemåte og påvirkning ved signalinterferens og spoofing.

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Maritime Education for a Digital Industry

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Abstract - The maritime industry is undergoing a digital revolution, and the high pace of change is expected to continue with the adoption of artificial intelligence and increased levels of automation on the horizon. These changes present many opportunities for innovation and improvements to the existing maritime industry, but they also pose a range of challenges. This paper will specifically examine the effects of these changes on seafarers, with regard paid to their education, and ongoing professional development over the length of a career. The evolving working context is resulting in the core skillset of seafarers to grow, particularly in relation to digital literacy. The January 2021 deadline of the IMO's cyber risk management Resolution MSC.428(98) has drawn attention to the capability and knowledge deficit in relation to cyber security within the industry's IT and OT infrastructure. As IT system grow in their usage and OT systems become more connected, and are modernized, seafarers need to still be able to use the existing technology, while becoming proficient in the new, creating a complex transition environment, with limited access or time to undertake professional development. This paper describes several new education approaches that are aiming to equip seafarers and other industry members to this changing knowledge landscape.

Keywords
Maritime Education, Digital Transformation, Cyber Security.

Introduction

The maritime industry is the backbone of global trade, handling 90% of long-range transport. The value of the goods transported is immense, with few other systems having as much impact on economies around the world. As a result, the safety and effectiveness of the entire maritime ecosystem is of interest to governments, regulatory bodies, businesses, and producers all around the world. As the system evolves, improvements can create more opportunities for trade, further fuelling economic growth. Conversely, threats to the maritime ecosystem can have broad impacts, slowing trade, causing massive economic losses. The blockage of the Suez Canal in early 2021, for example, was estimated to cost $9.6 billion US dollars per day of the blockage (Baker, Watkins and Osler, 2021). Concerns that face the maritime industry, which are of a systematic nature (those that effect the industry as a whole), are of great concern for the possible second and third order effects to the economies of countries around the globe.

The maritime industry, in its efforts to improve, has been becoming increasingly digitised in recent years. IT systems now have a significant role in bridge systems used in navigation, industrial control systems for controlling ship functions, eLogistics interconnections to enable effective transport in and out of ports, business and human resources systems, and personal use by seafarers. With these changes comes impacts that are positive to safety, efficiency, and wellbeing, but have also resulted in negative outcomes in the form of vulnerability to cyber threats, and a shift in the required skillset for personnel to operate vessels. The impact of IT systems is set to increase in the years ahead as connectedness of vessels increases, and as vessel operations adopt more automation.

This paper will explore the current state of affairs in respect to seafarer training in relation to the usage of IT systems, and discuss the current impacts being experienced within the industry. The paper will highlight several education and awareness efforts being undertaken by the authors to motivate change and improve digital literacy and provide cyber risk management skills across the sector. In addition, we examine the need for renewal of the training known as Bridge and Engine (aka Crew) Resource Management (BRM/ERM). BRM/ERM started its existence as a pragmatic approach to aviation incidents and accidents. At present it has a module on automation, but this is the application of BRM/ERM tools to a partially automated environment and it needs complementing or adapting to a more, or even fully, automated work environment.

Background

The maritime industry is rapidly digitising, undergoing a "digital revolution" (Nguyen, 2017). The changes are occurring at multiple levels within the industry, sometimes with differing motivations. IT systems are being used to undertake ship design and construction, seafarer training, ship operations and control, and within the supply chain. Such changes are not a surprise with many industries having undergone sizable change through the adoption of digital systems in the last half of a century. However, maritime, in some respects, is later to the wide scale adoption in some areas, and it is important to consider what are the likely effects on the industry as it adopts IT in ways it had not previously.

For example, in the early 2000s, the IMO mandated that all cargo ships over 300GT and passenger vessels implement the automatic identification system (AIS). The AIS system transmits data that describes the current state of the ship every 3-10s. While primarily a safety measure to assist in collision avoidance, this digital transition resulted in a dramatic increase of data available about ship movements and created multiple opportunities for innovation, particularly in green shipping (Watson et al, 2021), quite removed from its initial goal. However, unfortunately, AIS data has also been misused by pirates to target specific vessels (Wee, 2017). Technology can serve as a great catalyst for change, and the nature of that change is not always predictable – it can impact whether traditional approaches are changed, or indeed how seafarers interact with one another and vessel systems. While adopted for the expected benefits, of which there may be many, there can also be unforeseen challenges which also need to be overcome.

The digital change that is occurring within the sector will create new opportunities for the industry to innovate but could also present challenges to overcome.

Opportunity for Innovation

The digitisation of the maritime industry presents a broad range of opportunities. Sanchez-Gonzalez et al (2019) argue that the current advances are occurring in eight key areas:

- Autonomous vehicles and robotics,
- Artificial Intelligence (AI),
- Big data and analytics,
- Virtual and augmented reality,
- Internet of Things (IoT),
- Cloud and edge computing,
- 3D printing and addictive engineering, and
- Digital security.

Several of these areas, such as autonomous shipping and digital security, have been hot topics within the industry for some time and have also produced new guidance and regulations governing these areas within the industry (IMO, 2017; IMO, 2021). While others, just as commonly discussed, are resulting in shipboard systems evolving from being simple task-based systems, to also being key connected devices to enable digital shipboard and remote monitoring of a vessel, where previously this was not possible. This constant collection of data enables accurate models of performance of a vessel, or a particular system onboard, to be tracked and understood in far greater depth than ever before.

Indeed, across most of these areas, a common factor between many of them is an increased connectedness, and vast amounts of data are being recorded. This data is being used to drive the other areas such as artificial intelligence, to enable more productive use of existing systems. Many of the opportunities that are emerging are built upon leveraging data which were previously not recorded, or were too vast for effective analysis to occur, but thanks to technology advances is now possible.

Currently, AI, fuelled by big data, collected from IoT sensors installed throughout a vessel, can enable the creation of simulations relating to autonomous vessels, giving insight into what the future of shipping may be like. How automated these vessels may be remains to be seen, but, increased assistive technology, designed around AI produced models, that can be applied at the edge (i.e. on device, on board, possibly without external internet activity being required), is likely in the near future (Bergmann, Primor & Chrysostomou, 2021). The amount of data now able to be recorded and utilised, will undoubtably have a substantial change on how shipboard operations are undertaken. Inmarsat has reported that the data consumption per vessel increased nearly tripled, from 3.4 to 9.8 gigabytes between January 2020 and March 2021 (Thetius & Inmarsat, 2021), illustrating the transformation that is taking place.

A key element which could further accelerate this data driven future, is an external change in internet connectivity which is occurring over the next few years. Starlink, OneWeb, and multiple other companies, are in the process of recreating the satellite internet infrastructure used within the maritime industry. Instead of ships being reliant on low-bandwidth high latency connections, they promise a future of high bandwidth, with low latency (Scanlan, et al, 2019). Such systems will remove the bandwidth constraints which currently can limit the amount of data that is transmitted to and from a vessel while it is at sea. Once adopted, companies can make more use of cloud-based services and live data access to shipboard systems, and indeed can lead to adoption of systems like digital twins fuelled by this increased access to data. This will enable companies to further understand shipboard decision making and to train AI. An increase to the data flow in and out of a vessel will further accelerate the innovation cadence that digitisation has enabled to date.

The opportunities presented are rapidly translating into market value, with the last 18months of the

COVID-19 pandemic resulting in the digital portion of the maritime sector growing 18% more than previously projected (Thetius & Inmarsat, 2021). The global maritime digital technology industry is now forecasted to be worth $345bn by 2030, up from $159bn in 2021. This scale and rate of growth will attract new players to the industry, specifically technology and engineering start-ups, enabling innovation pace to remain high.

Challenges to Overcome

The increased adoption of digital systems is changing the maritime industry, and in particular the role that seafarers undertake. A selection of challenges directly impacting the seafarers include: need for new skillset, over-dependence on automation, security, reliability, and usability of the technology, and legal issues. (Earthy & Lützhöft, 2018). The possible changes are broad and have multiple impacts in how seafarers perform their duties. As such, a key element in the digital transformation is ensuring that, as systems are modified and evolve, designing them for their intended users is central to the process.

The introduction of AI as a truly intelligent colleague will likely be slower than many fear or anticipate but central areas of interest are how to cooperate (designing relationships such as teaming) (ISO, 2020), trust in, and trustworthiness of, the technology and issues regarding liability (Earthy & Lützhöft, 2018). This is a key example of considering human factors which impact how seafarers interact with AI driven systems that may replace or augment existing technologies. The role of trust within safety is a concept with a long history (Reason, 1998), and maritime specific obstacles have been articulated (Gausdal & Makarova, 2017). However, the adoption of AI, and the trust in those systems is a new context for the industry to adapt to. As seen in other sectors, trust and distrust in autonomous systems often leads to poor human decision-making, resulting in stressful and dangerous situations (Tam et al, 2021). Accountability practices will be a key element (Ariga & Sanford, 2021), however an education element for sea farers to understand AI systems capabilities and limitations is also important.

One of the most noticeable challenges being experienced due to the increased reliance of digital technologies, is an increase in cyber-attacks. This also has a trust element, in relation to seafarers being able to trust vessel systems are performing correctly, in the event of a cyber-attack such as a malware infection. This is made particularly challenging as often the source of the attack and its impact on operations is unknown. As shipboard systems become more reliant on sensors and digital systems, an attack could result in systems malfunctioning, or giving strange outputs, which are more subtle, and require critical thinking skills and IT knowledge to comprehend that an incident has occurred. There is also a need to develop trust between the crew and the broader shipping company to develop a just culture. Whereby crew are not blamed for mistakes, yet each member has a clearly defined responsibility in the event of a cyber-attack.

Since the dramatic effects of NotPetya on Maersk in 2017 (Greenberg, 2018), there has been an increase in cyber-attacks, with some estimates ranging as high as 900% across the last three years (Safety4Sea, 2020). The industry had previously enjoyed a relatively low risk of cyber-attack compared to other industries due to the disconnectedness of the systems, and with low digitisation. However, as digitisation adoption has grown, the cyber risk being experienced by vessels and companies has also increased. An argument can be made that cyber attack frequency will continue to grow as digitisation increases (Tuomala, 2021). As new satellite connections come online, enabling more data to flow in and out of vessels, opportunities for malicious actors to impact operations will also increase (Scanlan, 2019). In addition, as illustrated by the Maersk incident, the maritime industry exposure to cyber threats is not limited just to vessels. Shipping companies and ports are also targets of cyber-attack (de la Peña Zarzuelo, 2021). This is an industry wide challenge, which the industry has started to respond to, and will need to continue to in the years to come.

Most of these challenges, whether in relation to cyber security, or the impact of technology changes on seafarers, present a key role for education and awareness raising to mitigate the impact. As changes occur to work processes on vessels, whether it is in collaboration with AI, or whether it is undertaking work in a safe manner to minimise cyber risk, a training element is vital. As such, a recent maritime cyber security white paper found that 52% of respondents considered the human element as their organisations greatest cyber threat (Safety at Sea, 2020). This education element is not only likely a key part of the answer to the challenges previously described but are also a key challenge itself. Maritime is an old industry, with long established ways of operating and training its employees. A report from the World Maritime University (Schröder-Hinrich et al, 2019) states that with new technology, including increased levels of automation, will create new jobs and the requirements and skills needed for existing individual jobs will change. However, the digital revolution that is currently underway is moving quickly and can have direct impacts on to the safety of vessels and crew. Enabling rapid education and re-education of those within the industry is a complex problem, that is going to need a multifaceted solution.

Responding to the Challenges

The challenges that are facing the maritime industry due to the rapid digitisation that has occurred relate primarily to

- Increase in cyber threats
- Changed skill landscape for seafarers, both near term and further into the future
- A need for context and 'shape' of learning to fit around operational changes

There has been a sizable response to the cyber threats facing the industry, in part driven by IMO who amended the ISM Code to explicitly include cyber security by adopting Resolution MSC.428(98). The Resolution (IMO, 2017) encouraged ship owners, flag states, and others to ensure that existing safety management systems addressed cyber risks no later than 1 January 2021. This measure requires risk audits of systems to be undertaken, enabling much greater awareness to operators to the risks that are being faced, to facilitate mitigation measures to be implemented.

Furthermore, the Resolution explicitly states that under the objectives of the International Safety Management Code, there should be "…the continuous improvement of safety management skill of personnel ashore and aboard ships". As such, the ISM Code (IMO, 2018) stipulates that companies should establish and maintain procedures for identifying training which may be required in support of the safety management system. Thus, personnel must have the knowledge and skills to operate digital systems safety and securely during both normal and emergency operations.

In response to IMO's resolution, many nation states released additional guidance to enable operators to respond effectively to the cyber threat. In addition, a range of non-government organisations have also released guidance, including the following list:

- Baltic and International Maritime Council (BIMCO)
- Comité International Radio-Maritime (CIRM)
- Cruise Line International Association (CLIA)
- Digital Container Shipping Association (DCSA)
- International Chamber of Shipping (ICS)
- International Association of Dry Cargo Shipowners (INTERCARGO)
- International Association of Independent Tanker Owners (INTERTANKO)
- Oil Companies International Marine Forum (OCIMF)
- International Union of Marine Insurance (IUMI).

However, amidst all this guidance to ship owners and operators, it is vital to remember the human element: the seafarers, and their existing skill set. Already in 2018, the Norwegian shipowners' association encouraged the authorities to develop a strategy for maritime education with particular focus on digitalisation and to ensure financing for maritime and technical education. Several authors have highlighted the need for maritime education to be adapted within the current changing landscape (Sharma, Kim & Nazir, 2021; Heering, Maennel & Venables, 2020). A future where vessel systems operate with a level of autonomy, in a data driven environment, is distinctly different to the current context. Likewise, seafarers need to learn about the impacts of their actions on cyber risk to vessels and their operations. Heering, Maennel & Venables (2020) argue that not only is current education falling short of the need, but industry wide understanding of how the risks can impact vessels is also insufficient, with more research being needed to fully understand the skill requirements of different members of crew to provide adequate protection. Thus, more needs to be done to ensure the specificity of maritime cyber risk is addressed within new training measures.

The need for education across the industry, for ship owners, operators, and seafarers, is key to responding to the challenges. As the industry responds to cyber threats, as it evolves to be more data driven and utilise AI within its systems, there is a need to ensure increased awareness. Conventional education methods, such as Bachelor and Master programs, enable the skills of those entering or retraining to be uplifted. However, those who are not able to commit the time to such programmes require shorter alternatives that can meet their needs to attain the required knowledge and skills. The area of cyber security itself is one that has evolved quite quickly in other industries, and it presents an opportunity to try new education approaches, to increase awareness in an efficient manner, and with repetition as threats evolve.

These education and awareness measures need to be designed and implemented with the 'student' at the centre. Whether they are a conventional student, or a worker within industry undertaking an exercise for a few hours to fill a knowledge gap, the measures need to be flexible, engaging, and appropriate. As identified by the Maritime Skills Commission (Maritime UK, 2021) a change in approach to cadet training and skill uplift is needed across the industry, at all levels, so the response needs to meet the need where it is at. This paper explores a few examples of some education approaches currently underway, with a focus on cyber security, however the same initiatives could also be expanded to cover topics in autonomous systems, data analytics or human centred design.

Standard Training

We see a need to implement change at multiple levels within industry. A key component of the existing training is defined in STCW (Standards of Training Certification and Watchkeeping) and is known as Bridge and Engine (aka Crew) Resource Management (BRM/ERM). It was originally based on work undertaken in the aviation industry for flight crew (Flight Deck Resource Management - FDRM) and encompassed an eclectic mix of leadership, decision making, communication and emergency response concepts. As BRM/ERM became established in the shipping world there was little research into their content or learning delivery and the concepts were widely accepted (so much so that the ideas were encapsulated in the STCW (IMO, 2010) updates. The application of an aviation centric training to shipping has been criticized by Helmreich et al (2001), however, a more valid concern now is how suitable is BRM/ERM as it is currently defined, within a maritime industry embracing a digital and connected future.

Principally, non-digital attitudes and skill sets determine the content (and delivery) of BRM/ERM today. Furthermore, we have only apocryphal data supporting the present models; attitude, content and learning approaches. Indeed, regarding maritime training in a wider sense little research has been carried out into learning methods and content included. So today we find ourselves in a fragmented position (Hollnagel, 2021) both regarding content and learning approaches.

To align with other maritime developments, we must establish what role BRM/ERM has to play and what the contents need to be in order to accommodate the coming developments in (maritime) technology and practice. The curriculum needs to equip seafarers with the skills to interact with and understand data from a range of sources, with a strong focus on critical thinking to enable correct application and interpretation of the data. Increased autonomy within shipboard systems, creating a digital colleague, means that seafarers need to be alert and aware of the possible short comings of these systems, with the need for an increased focus on critical thinking within their education. The risks posed by cybersecurity incidents to crew safety, and vessel security, are also vital moving forward, and need to be included within any future version of BRM/ERM. In addition, it is vital to examine new learning methods and technologies, especially regarding learning approaches (a truly andragogical approach) and methods (gamification mentioned here, q.v.) such in the 'learning in the flow of work' (Bersin 2018), guided experiences (Billet 2000), 'blended approaches' (Friesen 2012) among others.

The developments in the wider corporate learning environment should be gleaned for those elements that can support an updated renewed content BRM/ERM, as should other domains so we build the best possible learner centric learning experience possible, that is truly responsive to performance needs and fills the space occupied by BRM/ERM. MOOC and game-based learning with simulation will provide motivating learner experience, but other methods need to be deployed as well to provide a lifetime immersive learning experience. Just as BRM/ERM content must evolve so must learning strategies. We need to move learning and content away from abstract knowledge into a learning experience which supports needful performance and is designed to achieve such.

The "shape" of learning needs changes. To provide better learning to the people working in this domain, approaches that consider the peculiarities of maritime work are needed. Increased flexibility, agility and support systems can help. More opportunities for multimodal education – alternate mechanisms to touch on key items, enabling less contact time but better outcomes in retention. However, more research is needed to understand what modes of education is best suited to deliver standardised training (such as that needed by STCW), and to enable workers already within industry to upskill around their work schedule. Such research needs to deliver solutions which scale across the entire industry.

Maritime Education Survey

A novel Bachelor program is underway in Norway which is co-taught across four institutions (University of South-Eastern Norway (USN), Western Norway University of Applied Sciences (HVL), Norwegian University of Science and Technology (NTNU), and the Arctic University of Norway (UiT)). The Bachelor of Maritime Management (BAMM) is taught to students who commonly already work within the industry, and study while at sea or on leave.

A cohort of these students, and several in related Master's programs, (84 in total) was surveyed to gain an understanding of the barriers they face with their study, and to give insight into the support provided by industry to those who are endeavouring to broaden their skillset.

A primary issue with students studying at sea was the lack of time to undertake study when on board (Figure 1, overpage). Over 50% of students reported only being able to study for 5 or less hours per week while at sea, whereas 85% of students reporting studying more than 5 hours per week when onshore. Granted, this is within a work environment, but there were multiple factors impacting their ability to work

Top rated common issues when studying at sea	Top rated possible solutions to issues
1. I find it hard to allocate time to study while I am at sea	1 Increased usage of 'at home exams' to enable them to be sat while at sea
2. The time schedule of classes rarely enables me to attend in real time while I am at sea	2 Increased flexibility around assessment deadlines - negotiated in advance of any time at sea
3. Submission deadlines are hard to keep track of while at sea due to a different routine	3 Course content is provided in advance of the start of classes in a downloadable form
4. The level of internet access I have at sea results in me not being able to access video content while at sea	4 A closer partnership between the University and the shipping company to foster support while to work and study
5. I find it hard to structure myself when balancing studies, work and everyday life	5 Each class has a group formed of those who are at sea, creating a peer support network
6. I find it hard to focus on work and study in the same day	6 A guaranteed time window by which all teaching staff will reply to emails
7. I find that my teachers don't seem to understand the difficulties that exist in studying while at sea	7 Increased focus on a stable set of features used across all units within the learning management system
8. I find it hard to work in groups when they are in different time zones to me while I am at sea	
9. I find it hard to follow pre-recorded lectures I have while at sea	
10. I find it hard to communicate with my lecturer via the learning platform while at sea	

Figure 1. Top ranked issues and solutions relating to studying while at sea by student respondents.

other than available time, including accessibility of content to study or limited internet access when they did have time to spend studying. These factors, when considered with time limitations onboard, and the need to context switch from work to study, presents a challenging study environment. Some of these issues are not easily solved and do require more support from industry – as only 15-25% of students get some consideration from shipping companies to their studies while at sea. However, other elements could be mitigated through proactive preparation and delivery of content (Figure 1). A high ranked solution was increased flexibility around assessment mode and delivery dates. Although another key solution, which is particularly relevant within a bandwidth limited context such as maritime, was for the content provided at the start of a study period. With the content ready before they go to sea, they will be able plan their study ashore and at sea to maximise their available time.

In late 2021 a range of these solutions were implemented within the delivery of BAMM. The bulk of the content was available at the start of the semester in written form – although recordings were posted once they occurred. Students were provided with assessment specifications at the start of the semester, with clear guidance as to what content within the course needed to be covered before they could attempt the assessment, effectively giving them submission windows that were weeks long, and could enable planning around shore visits. A time management resource was created, which consisted of a written piece giving advice on how to manage time, along with two different schedules tools, at different time scales, to not only enable them to plan ahead, but to also reflect across shorter time frames, to enable them to understand their studying capacity – with the intention of their becoming more informed of what they were actually capable of while at sea.

The students responded positively to the changes, and the same survey instrument was delivered after the teaching period to this cohort. There was a 25% (76% from 51%) increase in the number of students who stated that they felt supported in their learning, and 20% reduction in the number of students who didn't feel supported while at sea (from 26% down to 5%). In the ranking of problems that were experienced "I find it hard to allocate time to study while I am at sea" – fell from top ranked problem within the survey to third position. "I find it hard to focus on work and study in the same day" is the new top ranked option. The time management resource positively rated by all students who used the resource.

The students were asked how many weeks of the semester that they were at sea, and the average response was 4.8 weeks (with a wide variance (std: 3.2) due to some students not being at sea at all, with the most common time away being 8 weeks). The most any student was away during the 13-week run time of the course was 11 weeks. Having students who are not away at all, and others away for 80% of the course highlights the challenges faced within this cohort, and teaching those already embedded within the industry generally.

The survey has enabled greater insights into the challenges that face maritime students, and while it has enabled some improvements within this particular course, there is much more work to be done by industry and education providers to support students studying while they work.

MariMOOC

The transformation of the maritime industry into a digital industry is one that is rapid, and affects those who are already within the industry, and may have been for decades already. As such, conventional educational approaches, such as undertaking a degree at a university, is a substantial barrier for them to attain skills or awareness of the kinds of issues most relevant to them during this current transformation.

In response to this a Massively Open Online Course (MOOC) was proposed and then constructed, with it launching in 2020. The MOOC covers a broad range of topics, but is primarily focused on Maritime IT, and in particular cyber security. In order to put IT skills into context, the MOOC also gives an introduction to human factors design principles and a look at technologies of the future such as autonomous shipping. Learners are able to study the content following multiple pathways, with it divided into 4 chapters that can be completed in any order.

The MariMOOC aligns with an xMOOC design, meaning an eXtended Massive Open Online Course. This style of MOOC aims to deliver content which could be delivered within a university setting, but is being offered online with the overarching goal of significantly broaden the number of students who can be exposed to university-level courses. xMOOCs reflect education theories such as instructivism (Jordan, 2014) and cognitive-behaviourism (Admiraal et al., 2015; Bali, 2014) As such, it is focused on instruction on defined topics, through multimedia by an educator. Peer based learning is not central to the approach, enabling students to work to their own timelines. Primary learning outcomes are tied to given tasks with clear instructions – enabling a learner to follow the course without outside assistance. Such a system also enables a competency model of assessment to be applied, which is seen as less arduous than written or exam-based methods. Such a shift is argued to be more accessible to students who have spent a period working in industry or away from educational institutions, while still achieving the same assessment goals. The fully online model of a MOOC provides a great deal of flexibility in relation to the speed at which a student can undertake the course, enabling them to go at their own pace -starting and stopping around other commitments, and not tied to a semester timetable.

To date the MOOC has been trialled with several industry partners and has been undertaken by over 100 learners. The MOOC is being shared with industry partners directly and is able to be imported into existing learning management systems as a standalone course.

Game-based Learning

Simulator training within the Maritime industry has been around for decades, with its origins in the 1970s (Homlong et al, 2016). As computer power has increased, the fidelity of the training environments has improved, and as costs have decreased it has also presented additional opportunities to leverage simulation-based training in more contexts (Mallam, Nazir & Renganayagalu, 2019). Examples of this, including using consumer grade AR or VR systems, can be used instead of large room sized custom built environments, leveraging the lower cost to provide educational outcomes in areas not previously focused upon for simulation.

Several of the authors of this paper are currently creating a serious game (i.e a game built for a non-entertainment goal), which can be used in VR or in 2D within a web browser. The intention is to provide a simulation-like environment, at very low cost, available to seafarers wherever they are physically located. Requiring only a laptop, instead of a complex expensive simulator, enabling topics such as cyber security and human factors to be the focus, which is quite different from the traditional simulation environments used for navigation and other vessel operations.

The game environment is being designed and built as flexibly as possible, with multiple scenarios being planned for the future. The current focus is on meteorology and cyber security. The former, for which the VR environment was initially conceived, enables a learner to experience weather conditions as described by the Beaufort Scale (Saucier, 1955). The learner can walk around the environment, and from the bridge of the vessel they can select the current level on the Beaufort scale. The weather within the game environment changes, resulting in the waves buffeting the vessel, effecting in game physics, with other weather effects also being visualised. Within VR it is quite disorientating, due to the immersion effect of the learner's entire view being the game environment – which itself does not watch their real physical surroundings. The intent, once complete, is to illustrate the consequences of weather in combination with navigational choices, and how ship and crew are affected by different weather types.

Building on this same game environment, and in alignment with the pressing needs as described within this paper, a cyber security educational game is also being developed. This is scenario based, and as the learner walks around the vessel, and enters into areas such as the bridge, office or mess, they are presented with pre-scripted scenarios which relate to cyber risk. The learner has multiple options to respond to the scenario, deciding how to act or respond. The learner is informed as to the outcome, but also the repercussions of an incorrect outcome, and how it may affect the vessel. The aim is to explore not only the root causes of cyber incidents, such as how malware may get into a system onboard, but also what are the possible outcomes and the effect on the learner and other crew on board. Understanding the impact, large or small, on the vessel or the quality of life of seafarers, is seen as an important step to motivate behaviour change in relation to activities with a cyber risk.

The game-based learning approach described above is being developed as an additional alternative to more conventional education approaches. It can be embedded within existing curricula or be shared between possible learners within industry in a standalone form. It provides a short, immersive, goal orientated education artefact, aiming to express core fundamentals that are relevant to the human element within cyber risk management on board. The game-based elements aim to increase engagement to promote learning (Hamari, 2016). Many awareness protocols and education activities can be policy driven and can lack explanations as to the impacts if policies are not followed. The game-based environment is aiming to be facilitate cultural change through explaining the impact of cyber risks within the working environment, in a novel manner to attract attention to the challenges that are currently being faced.

Cyber-SHIP Lab

The latest version of the industry-published Guidelines on Cyber Security Onboard Ships (BIMCO, 2020) highlights, the broadening risk landscape facing digital bridge systems. However, there are a lack of suitable research and mitigation capabilities available to educate the sector about these risks. This gap led to the development of the Cyber-SHIP (i.e. Software, Hardware, Information, Protection) Lab. The lab hosts a range of real, non-simulated maritime systems, which is capable of configuration to match real-world bridge integrations (Tam et al, 2019).

Through the lab's ability to run controllable and safe experiments on maritime systems, companies can learn more about their bridge systems integrations, interactions, and risks. These experiments include a range of penetration testing tools, and the running of known, and potentially custom malware. The findings from these experiments will build a detailed picture of the vulnerabilities that specific bridge integrations have.

These findings allow the Cyber-SHIP lab to offer various opportunities for improving maritime education and security education. Firstly, the initial findings from the vulnerability assessments will educate the company of the cyber risks that they face. Thus, allowing them to implement appropriate mitigation measures, including cyber security training. Secondly, these findings can inform the development of simulator-based training exercises. As discussed above, the maritime sector has a long history of benefiting from simulator training with crews (Kobayashi, 2005). When used as part of crew training and awareness programmes, these simulations will allow companies to train personnel, and test their incident response practices. What is more, crews can gain first-hand experience of a "real" cyber-incident, in the safety of a simulator.

Cyber Ranges

A cyber range is a simulated environment designed as a representation of an organization's ICT, operational technology and physical systems, applications and infrastructures (NIST, 2020). These tools allow companies to create specific network topologies and employ a range of tools and attacks without risking the organization's actual infrastructure (Priyadarshini, 2018). One such tool allowing the development of a simulated environment is the EU's Cyber-MAR. The platform aims to provide companies with a way to educate themselves about cyber risk (Cyber-MAR, 2019).

To ensure the simulated environment is as realistic as possible, companies must develop a very detailed understanding of their own networks. Once modelled, the tools within the platform allows a company to educate themselves about their network interactions and how these could lead to vulnerabilities. Again, this understanding can then be used to inform the design of maritime education programmes. Thus, ensuring that personnel are provided with the skills and knowledge that is appropriate to the risks they face.

Furthermore, utilising a cyber range as a training tool has other benefits, one of which is federation. Examples of federation includes the support for running simulations and activities in multiple locations and sharing those activities with others (Tam et al, 2020). Thus, allowing companies to develop and deliver cyber range-based training in different locations. A particularly useful attribute considering the often dispersed geographical location of a company's maritime assets and personnel.

Conclusion

The maritime industry is changing, and with that change, as described in this paper, are many positive outcomes, but also several challenges. The education needs of the sector have shifted, and will continue to shift, as the current digital transition continues, and indeed may accelerate. A key area in relation to this is cyber risk management. IMO, and others, have taken steps to lift the capacity of the industry to meet this challenge, but central to this response needs to be equipping seafarers to play their role. A safe and secure shipping industry requires many within the industry to adapt their skillsets to the new landscape. This is a significant educational and awareness challenge. The current skills gap in relation to cyber could be just the beginning of a shifting skills landscape with a future that is more reliant upon data and automation.

Enabling an industry to respond to a new set of risks which it has not had to deal with before requires a substantial effort. There is the need for technological innovation to meet the risks, but also for cultural change to ensure the challenges are given an appropriate level of resources and attention. The educational needs within the sector are shifting, creating skill and awareness gaps. Those working within the sector already have existing workloads and priorities and cannot simply dedicate substantial amounts of time to training courses. The approaches need to be flexible to the time pressures that are present, while still providing meaningful outcomes.

This paper has described several initiatives which aim to meet this challenge. They are focused on raising cyber risk awareness and educating how to manage cyber risk in a maritime context. There is no single solution, and indeed only several possible solutions are presented here. It will require an industry wide effort to ensure the digital systems being used are used in a safe and secure manner. A possible solution is to revisit BRM/ERM and establish what role it can have in providing a firm foundation in skill requirements required for those within the industry. An updated BRM/ERM could define a baseline of skills and awareness in relation to cybersecurity, providing a more defined framework for shipping companies to work within to maintain a highly skilled workforce.

A future where vessels have an increased level of autonomy, will also change the skillsets of seafarers and others within the industry. Many of the education initiatives and methods described here, in relation to cyber security, can be seen as a 'practice run' for the further changes which will occur in the years ahead.

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Applications of Maritime Simulators in Industry and Research

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Abstract. Ship-bridge simulators are ideal arenas for research and innovation, hence, the use of simulators in industry and in research is ramping up. Ocean industry prospects are addressing core challenges such as food, security, energy, and climate change. The ocean holds the promise of great potential for economic growth. Appropriate tools are required for answering the questions of the emerging ocean operations. Questions related to technology development, training, safety and efficiency rise on a daily basis, where ship-bridge simulators could be the labs facilitating a wide spectrum of research experiments. This paper presents the role simulators play in maritime operations and lists various applications of ship simulators according to a literature review and nine interviews with researchers and managers in simulator centres. It also presents a case study of the current and future uses of simulators by the Norwegian Coastal Administration Pilot Service. The scope of simulator applications is wide, beside training, they are used in development of autonomous controllers and in recruitment of pilots.

An accuracy concern is identified; simulators must hold an appropriate level of accuracy to fulfil the different application objectives. The standard for Maritime Simulator System, DNVGL-ST-0033, does not recognize applications other than training. In addition, it requires no objective assessment of ship dynamics, as required by the flight simulation standard (CS-FSTD).

Keywords: Ship Simulators; remote control; accuracy requirement levels

1 Introduction

Simulations and simulators have been applied in engineering for few, even several, decades. It is the maritime domain that is transforming towards a highly digitised industry, from research, training to operations, the dependence on digital systems is increasing. On top of that, the exhaust emissions regulations are getting stricter every five years according to the Marine Environment Protection Committee of the International Maritime Organization (IMO - MEPC, 2020). This tightening of the emissions regulations is challenging all the sectors involved in the shipping industry to strive for higher efficiency. Therefore, research is a key for solving such challenges and hence, simulators are methodological enablers for future potential solutions.

The strict regulations do not only challenge ship engine and fuel type. They also challenge routing, the understanding of weather systems and environmental loading along the planned route, hence the selection of the route with minimum loading yet satisfying time and emissions constraints. The regulations also challenge the manning of ships as with reduced manning the hotel loads are reduced and thus the emissions are reduced, this brings attractiveness to the concepts of remote control and higher lev- els of autonomy in the shipping and offshore industries. This cascades into human fac- tors challenges of how teams can work together for an operation while dispersed, with parts of the team sitting in different places in the world, and so on.

In all mentioned challenges, simulations and simulators can play a role. However, because the nature of the challenges is broad, it is not clear who is using ship simulators and what they are using them for. This article aims to present an overview of the use of maritime simulators. The introduction covers background information on simulations, simulators and the industry trends of utilising them.

1.1 Simulations and Simulators

In short, simulations try to mimic real-life. The concern could be a real-life response such as in the case of fire drill, or it could be a real-life phenomenon, such as the elongation of a metal rod when heated. In the latter example, mathematical models are used to calculate the heat transfer and thus the thermal expansion of the rod. Using a computer simulation that can also take time into consideration, the phenomenon can be explored virtually on the computer. This opens the opportunity to investigate what happens if the heat source is changed, and similarly, if the type of metal is changed.

Computer simulations offer practical and convenient features. They enable running the 'virtual test' many times in fraction of the cost compared to physical testing. They allow for affordable 'testing' of extreme conditions, say, very hot temperatures that are hard to achieve in your lab's furnace. They also can be connected to other computer simulations building a mega simulation estimating multiple physical phenomena and their interactions.

Some computer simulations are designed to provide the user with a virtual experience. These are called simulators; they interact with human inputs and present the responses as they evolve on screens. Some maritime simulators are designed to provide a very immersive experience, with 360° curved projection-screens and, few of them have moving platforms. Recent generations of maritime simulators are quite immersive, the visuals are seamless high-definition projections, in a room with hardware that is identical to that found in real vessels (O. Hareide & Ostnes, 2016). Users of such simulators have fully furnished bridges including chairs, propeller levers, rudder control, radar, electronic chart displays, radio communication device, etc, as if they are on a real ship. For example, check the latest ship bridge simulator solutions of Kongsberg (K-Sim) or Wärtsilä (Transas).

As described by (Porathe, 2016), *"A ship-bridge simulator is a piece of laboratory hardware and software that simulates a ship's behaviour from the vintage point of its bridge. Often consists of a mock-up bridge (a more or less realistic bridge interior with consoles, screens, instruments and windows to the outer world) but often also a visualization, i.e. the egocentric 3D view of the surrounding world with ships, islands, and ports projected on screens outside the windows".*

1.2 Practices and Training

Involvement of maritime simulators in both academia and industry is becoming more visible. The following are examples on national and international collaborations involving the use of simulators for advancing maritime operations:

- SFI MOVE (*https://www.ntnu.edu/move*), a Center for Research-Based Innovation for Demanding Marine Operations is using simulation-oriented approach to solve some of the pressing challenges in the offshore industry. The centre has been running for several years. This centre is an example of academy-industry collaboration for solving real-world problems using research in simulators (*SFI MOVE*, 2016).
- EU project AutoShip (*https://www.autoship-project.eu/*), where simulators will be upgraded to better support testing, commissioning, training and operations of autonomous ships (*AutoShip*, 2019).
- SFU COAST (*https://norway-coast.no/*), A Centre of Excellence in Maritime Simulator Training and Assessment envisioning the innovative potential of the best simulator practices in maritime education (*SFU COAST*, 2020).

Ship-bridge simulator-based training practices are well established in maritime education. The International Convention on Standards of Training, Certification and Watchkeeping of Seafarers (STCW) of the IMO regulates the standards of training. The main purpose of the Convention is to promote safety of life and property at sea and the protection of the marine environment to ensure that future professional mariners can operate properly and safely in their work practice, this convention emphasises on the use of simulators for both training and assessment (STCW, 1995).

For example on the use of simulators for maritime education, the set of simulator-based training courses offered by IMO, for both the novice and the experienced participants includes, but not limited to, the following simulator courses listed in **Table 1**.

Table 1. Some of the simulator-based training courses offered by the IMO (STCW, 1995).

1.	Ship simulator and bridge teamwork	2.	Liquefied petroleum gas (LPG) tanker cargo
3.	Liquefied natural gas (LNG) tanker cargo	4.	Oil tanker cargo + Ballast Handling (BH)
5.	Chemical tanker cargo + Ballast Handling (BH)	6.	Automatic Identification System (AIS)

In June 2015, after a series of EU projects from 2009, the IMO approved a "Guideline on Software Quality Assurance and Human-Centred Design (HCD) for e-Navigation". The objective of e-Navigation concept is to harmonise the collection, integration, exchange, presentation and analysis of marine information by electronic means to enhance the operations and their safety. IMO considers that e-Navigation should be user driven rather than technology driven. HCD methods require heavy involvement of seafarers and operators in the design and development process of navigation aid tools. From 2015, the IMO recommends that HCD should be used in development of new navigation equipment (MSC, 2015).

As the HCD guideline encourages the involvement of users in the design process, it also, indirectly, encourages the use of simulators in that process. The simulators can play the role of labs, for testing out the new product being under development, for measuring the user experience and user satisfaction while using the product, and for measuring the performance of the user in a virtual operation using the product. Thus, simulators can be used for testing and validation of design concepts enabling effective HCD processes.

According to DNVGL-ST-0033 (2017), the Maritime Simulator System Standard, ship simulators are classified into four groups. Class A (full mission), B (multi-task), C (limited task) and S (special task). In addition to the classes, different types of ship simulators exist, based on the type of functions they simulate, the types are listed in **Table 2**.

Table 2. Ship simulator types based on operation type (DNVGL-ST-0033, 2017).

1.	Bridge operations	2.	Machinery operations
3.	Radio communication	4.	Cargo handling
5.	Dynamic Positioning (DP)	6.	Safety and Security

7.	Vessel traffic services (VTS)	8.	Survival craft and rescue boat
9.	Offshore crane & Remotely operated vehicles (ROV)		

To sum up, simulators are not only used for training; they are also being lately used for research, design, and other applications. An overview of the use of simulators is presented herein, with focus on their use as a research tool. In addition, an overview of the opportunities and challenges associated with their usage is also presented. Hence, this article is a contribution towards answering the following questions:

- What are simulators used for?
- What are the opportunities and challenges of using them?

2 Methods

To answer the two questions above, three methods have been used. First, a literature review for relevant research that uses simulators, second, interviews with professionals and researchers in the field, and third, a case study with a relevant industry player. Details about the three methods follow.

2.1 Literature Review

The literature review is made to contribute mainly to answering the first question: "What are simulators used for?" from the research perspective. A literature search has been undertaken in the search engine "Oria" of the Norwegian University of Science and Technology (NTNU) that provides search of the university's both printed and electronic collections of internationally renowned scientific databases (and publishers) such as INSPEC (Journal of Navigation), Scopus (Elsevier, Springer, IEEE), ProQuest, TransNav and WMU. Searching for literature on the search engine Oria has been done without specifying certain databases. Only literature reporting use of navigation simulators are selected. The search criteria of the literature review are found in **Table 3**.

Table 3. Literature review search criteria

Keywords:	Ship simulator; bridge simulator; mission simulator
Publication date span:	12 years (2009 – 2021)
Material type:	Articles, journals, and conference proceedings
Filters:	Publications that do not involve use of simulators (removed)
Selection size:	80 publications (selected after applying the filter)

2.2 Interviews

Subject matter expert (SME) interviews are held to bring a variety of perspectives from both researchers and professionals in the field. A Google search was made for both academic and commercial simulator centres all over the world. Thirty-five centres were identified. A shortlist of contacts was created for interview invitations. Ten positive responses were received and actually nine interviews were performed. Five interviewees are researchers and four are managers at simulator centres. The interviewees have different backgrounds, seven of them are engineers and two have social science backgrounds. At the time, the interviewees were geographically located as follows: 5 were in Norway; 2 in Sweden; 1 in the Netherlands; and 1 in Canada. All the interviewees referred to maritime simulators in their interviews, most of them (seven out of nine) referred to full mission navigation training simulators (Class A) and the rest referred to offshore operation simulators (Class S). The interviews focused on, and started with, the interviewees' work and experience, shaping an interviewee-centred context throughout the conversation.

The interviews were designed as semi-structured interviews with open-ended questions. The duration of interviews was half-an-hour on average for each, which started with an introduction about the interviewers and their motivation for conducting this research. Inductive coding method is used for analysing the collected data. The interview questions are as follows:

1. Tell us about yourself and the field of your interest.
2. What opportunities do you think simulators provide for research (or for the industry)?
3. What challenges have you faced while using simulators for your research (or for your work)?

The inductive coding process was performed in two levels, the general themes, and the more specific items, nested under the themes. Responses were compared across all interviewees for each question at a time. Similarities among the answers were identified and were given labels for the general themes they address, such as "research and innovation facilitator" and "developing industry standards" labels for the second question about opportunities. There were three labels identified for each question. The labels describe the general themes and provide a rough description of the interview results. A higher level of detail was needed to convey the picture the interviewees painted, therefore, specific items where identified and coded. Every labelled theme then was described by several coded items. For example, in the second question (about opportunities), nested under the label "research and innovation facilitator" the following codes were given: "innovation facilitator"; "multidisciplinary"; and "proof of concept". The codes are, in most cases, self-explanatory, and provide additional level of detail to the description of the interview results. The coded items aid the labelled themes in describing the content of the interviews, and together they provide answer to usage, opportunities and challenges as presented in **Table 5**.

2.3 Case Study

The Norwegian Coastal Administration Pilot Service (NCA PS) is selected as a case study for an intensive investigation regarding their day-to-day operations and their approach to using simulators, and maritime technologies, for solving today's and tomorrow's challenges. The information is collected mainly in a webinar that is designed for the purpose of this study. The webinar was held on 19 January 2020 and was named "Learning from the Pilots". The agenda of the webinar included the following sessions as listed in **Table 4**.

Table 4. Learning from the Pilots webinar agenda

1.	Short introduction from the NCA
2.	Everyday life of a pilot
3.	"Sleipnir" platform to Haugesund operation
4.	Recruitment and simulation
5.	R&D strategies of the NCA
6.	Open discussion

The design of the webinar included long questions/answers (QA) sessions. In addition, participants, who were mainly students and researchers, were encouraged to ask. The active participation in the QA sessions was modest therefore the collection of data was mainly passive.

The interviews took place in April 2019. The literature search took place from February to April of the same year, and later the search was complemented in the beginning of 2022 to include relevant research that was published within and after the year 2019. Within the 2019, the main author participated in a research work that aims to develop a decision support tool that aids navigators in selecting the proper rudder angle for the coming turn (Dimmen et al., 2020). The decision support tool was tested in navigation simulators and the conclusion was that such a tool can help navigators in close quarter maneuvering. This conclusion motivated the author to pursue collaboration with the Pilot Service to learn about their use of technology, seeking confirmation (or rejection) of the previous conclusion. Apparently, the Pilot Service were also motivated to collaborate with researchers and eager to increase their use of technology to advance their operations. Therefore, as a first step in the collaboration, the webinar "Learning from the Pilots" was suggested. The webinar was not meant to answer a specific question, on the contrary, it was designed to convey as much as possible from the pilots' experience and challenges. Such information serves as a necessary background for the creation of different research sparks. In addition to that, supplementing this article by providing a detailed contribution on their use of simulators.

3 Results

The results are presented in this section. First, results from the literature review, second, from the interviews, and third, from the case study.

3.1 Literature Review

Starting with describing the demographics of the collected literature. It is observed that 63% of the reviewed literature belongs to the Natural Sciences, 25% belongs to the Social Sciences and the rest can be identified with both scientific branches. It is also observed that 54% of the literature is using Quantitative methods, 26% is using Qualitative methods, while the rest is using mixed methods. The literature is classified into five groups. Fig 1 includes the distribution of the literature into the five groups: Development; human factors; training; learning; and risk analysis.

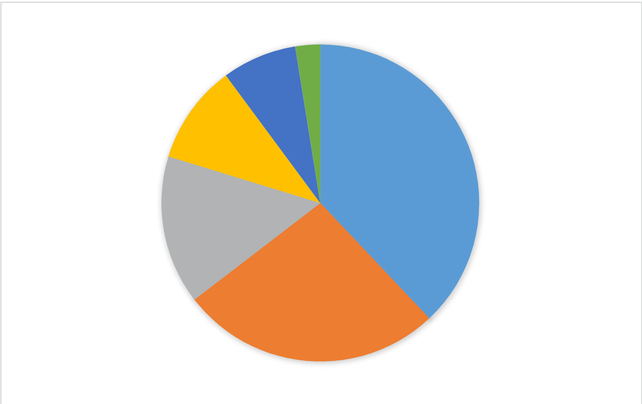

Fig. 1. Literature classification

Development

This group constitutes of 38% of the literature. This group is using the simulator as a step in the development or evaluation process. Most of this group is developing programs / algorithms that enable autonomous maneuvering, and they are using the simulator to present their development program, or to evaluate it using the human-in-the-loop concept. In the literature, the development group is not limited to products (such as programs / algorithms), it also includes development of procedures and specifications. For example, Ari et al (2013) developed a path planning algorithm that is length-optimised and feasible regarding turning radii of the given ship. They demonstrated a proof-of-concept of their algorithm using a ship simulator experiment. Varel and Sores (2015) on the other hand, developed a simulator program that is built specifically for training on ship-to-ship offloading maneuver. Their research constitutes basically of presenting the development works and final product. Hareide and Ostnes (2017) however, developed a navigation procedure that is inspired by a simulator experiment. They performed a simulator experiment with eye tracking devices. They identified efficient scan patterns and developed scan patterns for maritime navigators that maximise safety. Lastly, it is observed that virtual reality (VR) simulator development studies are emerging (Jinlong, 2019; Lauronen et al., 2020).

Human factors

This group is the second largest, constituting 27% of the literature. This group is mainly researching the human operator inside the simulator. The focus is on either the human experience, or the human performance. More than half of the literature in this group use physiological monitoring as part of their data collection methods. They measure either heart rate or brain signals to gain understanding of the workload or stress level the operator is experiencing in real-time. For example, Hontvedt (2015) introduced a study that examines the experience of professional maritime pilots in a simulator training exercise using azipod propellers to navigate in high winds. The participants reflected on their experience in debriefings. The interaction analysis performed by Hontvedt shows that simulator training has distinct advantages, however, the pilot's experienced lack of photorealism and graphical fidelity in that simulator and this could compromise the effectiveness of the training. Orlandi and Brooks (2018) also evaluated the experience of marine pilots in a berthing operation exercise. They used both qualitative data, such as the self assessment scales, the NASA TLX and the Likert scale, and quantitative data from Electrocardiography (ECG), Electroencephalography (EEG), and eye tracking. They demonstrated that they could indirectly monitor levels of mental workload as they develop over time in a demanding operation. Lastly, Nilsson et al. (2009) presented a study similar to Orlandi’s, evaluating the performance of marine pilots, in two different bridges, one with more advanced instruments, and the other with less advanced technology on board. They used several data collection methods, both qualitative (questionnaires and expert opinion) and quantitative data (physiological sensors and response times). They concluded that performance is not clearly correlated with the level of technology on board, however, if mariners' experience is taken into consideration, they found a link between experienced navigators performing better in less advanced bridges and less experienced navigators performing better in more advanced bridges.

Training

15% of the literature belongs to this group. This research mainly demonstrates the potential of simulators in training of operators to achieve higher levels of safety or efficiency. Some consider training for higher energy-efficiency and lower emissions, some consider training for a specific maneuver such as the man-overboard Williamson turn, and some consider training in specific conditions such as shallow water maneuvering. For example, Benedict et al. (2014) presented their development of an innovative simulator that presents future projections of a ship’s path according to current conditions. This could be classified in the development group, however, they emphasised on the value of their developed simulator in training, elaborating that it can be useful in briefing and debriefing sessions for ship handling simulator training, and that it can be used as a training tool on board ships. Jensen et al. (2018) presented a proof-of-concept of a training that is helpful in saving fuel. They stated that fuel-efficiency of ships is not merely a technical concern, they showed that awareness, knowledge, and motivation are also important parameters in fuel consumption. Lastly, Formela et al. (2015), on the other hand, used a maritime simulator to train candidates of two different man-overboard maneuvers. Their investigation concluded that the Anderson Turn is more efficient than the Williamson turn.

Learning

10% of the literature belongs to this group. A group of literature that uses the simulators in their research to focus on learning. The difference between training and learning in this context is as follows: Training describes the use of a simulator for nautical students and experienced professionals to enhance some of their relevant skills. However, learning describes the use of a simulator to understand the process of knowledge transfer (and skill transfer as well). This includes education science, the actions that contribute to learning, including the role of the instructor in briefing, debriefing, or during the exercise. For example, Hontvedt and Arnseth (2013) are researching the learning in a simulator. They are investigating the context in which students and instructors collaborate to achieve learning goals. The study shows that the collaboration and meaning making of students is an important entity to address in the design of simulator exercises. In addition, Sellberg (2018) has performed an ethnographic study to investigate the instructor role in a simulator exercise. The research shows that a continuous instructional achievement, from briefing to in-session instructions, to debriefing is highly important to facilitate learning towards a profession.

Risk analysis

A minor group that is grabbing attention in recent years, a group of literature that uses the simulators in their research to focus on safety. Statistical methods for calculating collision probabilities are common here. Some studies do reconstruction of previous accidents, such as the 'Ever Given'grounding in the Suez Canal. Others develop practices that aim for a reduction in risk, for example ship-whale strike risk. For example, Popov et al., (2021) held an investigation based on a reconstruction of the Ever-Given grounding incident in the Suez Canal in a ship simulator. Grende et al., (2019), alternatively, proposed a set of practices for reducing ship strike risk as an active whale avoidance strategy and tested its feasibility in the simulator.

Research in ship simulators is multidisciplinary. The research fields of the main authors (of the collected literature) are noted. A variety of disciplines are involved, the leading discipline herein is Ocean / Naval Engineering, followed by Teaching / Training; Safety Engineering; Computer / Control Engineering; Industrial / Civil Engineering; Psychology; Human-Computer Interaction (HCI); Social Research; Mathematics;

and others like Finance / Economics; hydrodynamics; fishery and aquatic disciplines. The distribution of the main-author-disciplines is presented in **Fig. 2**.

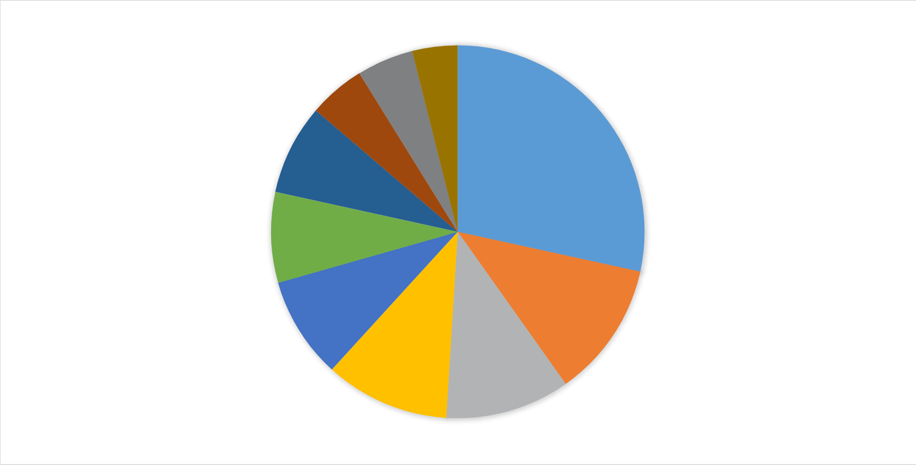

Fig. 2. Disciplines of main authors of collected literature

3.2 Interviews

The interview codes are found in Table 5. The main usage of simulators according to the interviewees is related to education and training. However, interesting applications are emerging such a sensor fusion of physiological data and the testing of technology and algorithms for enabling autonomous operations become safer than conventional ones.

The opportunities are summarised in three main points. First, simulators are facilitators of research and innovation. Second, simulators stimulate change in industry workflows. Third, simulators open new frontiers towards transforming the industry.

All researchers have agreed on the research infrastructure challenges, such as the availability of simulators and the availability of some expert helping hand to aid them throughout their experiments. While the managers mentioned issues related to cost of handling and maintaining simulator facilities. Interviewees using offshore operations (Class S) simulators were more innovation-oriented in their answers focusing on simulators' role in development of products and development of industry workflows. Elaboration on the results follows in the discussions section.

Table 5. Interview codes

Q1: Usage	Q2: Opportunities	Q3: Challenges
Education and training • Performing demanding tasks • Individual and group training • Training novice and professional • Leadership training • Joint situational awareness • Enhancing safety and efficiency	**Research and innovation facilitator** • Innovation facilitator • Multidisciplinary • Flexible scenarios • Connect simulators together • Autonomous docking • Complete control of situation • Proof of concept • Huge savings • Human factors: teams/genders/cultures • Training of algorithms/people/procedures • Observing the experts	**Research infrastructure challenges** • Availability of simulators • Availability of participants • Availability of technical support • Availability of maritime research partner • Data management • Availability of hardware
Reseach in education • Learning curves • Research "learning" • Instructor role	**Developing industry standards** • Development of design methods • Validation of new methods	**Simulator being just a simulator** • Limited setup flexibility • Duration of simulation • Location of simulation • Simulator maintenance cost • Bugs and shutdowns
Research in technology • Collecting physiological data • Testing interaction • Data driven models • Human/hardware in the loop	**New frontiers** • Harsh environments • Autonomous vessels • Testing rare scenarios	**Technology readiness** • Sensor technology • Validity and reliability • Physics in co-simulation

3.3 Case Study

This section lists simulator applications according to the Norwegian Coastal Administration Pilot Service (NCA PS), followed by a bullet-point highlight of their research and development strategy.

Simulator applications

Five simulator applications according to the NCA PS are listed below:

I. During the preparations of the pilotage of Sleipner platform into Haugesund port; that is a maneuver with a huge platform and tiny margins. Part of the training for this operation took place at Heerema simulator centre.

II. In the recruitment process, the NCA shifted their focus towards people skills, learning ability and the ability to acquire knowledge. Since 2018 the NCA is using, among other tools, simulators at NTNU to achieve this objective. They use general mental abilities (GMA) tests, personality tests, ability and skill tests, stress tests, structured job interviews and simulator exercises. In the simulator exercises, factors such as blackouts, lack of GPS, gyro-errors, and ocean currents are inserted into the scenarios to make them as challenging as they can possibly get in real-life. The NCA is using a panel of pilots, pilot director staff members, HR consultant, and the leader of the pilot district, which is a widely exposed assessment group, structured assessment forms describing what to evaluate and occasional pauses are scheduled to adjust the candidates and give them feedback and see if they can learn from their earlier mistakes. Correspondence between previous tests and real time impressions are checked. A lot is revealed about the candidates, and simulators create a suitable environment for research. The NCA's practical experience with simulators for the final cut assessments is that simulators are well suited; for they unveil the candidates' strengths and weaknesses. Still, the NCA would need to have objective ways of measuring candidates' conditions (pulse/stress/forms) and assessing candidates' overall performance.

III. Simulators are used for safety critical port operations. Ports are the same, ships are increasing in size, weather is sometimes harsh, simulators can be used to test external limits to operations that may have previously been deemed too risky. Simulator port studies consist of**:**
   - Risk assessments: define a given risk for a vessel on arrival / departure under various meteorological conditions.
   - Mooring analysis: identifies mooring opportunities towards the harbour, the risk associated with this and the outer meteorological limits of the mooring. For ex: "*can MS lona at 340 m length berth in Stavanger with 35 knots wind?*"

IV. Simulators are used for operational training (demanding operations). Can be a general training or a specific training. Can focus on technical skills, coordination, cooperation, leadership, and/or communication. Can be general training such as ship handling, tug courses, VTS, and bridge resource management (BRM) courses. Can be specific training on predefined assignments such as the entering and leaving of Nexans in Halden. Can be training for distribution of learning across the organisation, organisational culture, and safety culture.

V. Ship handling training through virtual reality simulators. The NCA is developing a VR simulator with adaptable ship models for pilotage training in advance of the real operation. Beside that, this tool can be used for BRM, teamwork and risk assessment studies.

Key areas for NCA's R&D strategy.

- Bridge Resource Management (BRM)
- Pilot – Vessel Traffic Service (VTS) co-operation
- E-Navigation (enhanced navigation such as decision support using digitalization)
- Sensors and sensor technology
- Safety culture

- Recruitment and leadership

4 Discussions

The results from the three data collection methods are merged into a mind-map showing the extent of the usage of maritime simulators. The applications are categorised in 6 categories as such:

Fig. 3. Simulator applications mindmap.

i. Education and training
ii. Operator training

iii. Assessment
iv. Development and testing
v. Research and innovation
vi. Digital twins

Where, AIS: Automatic identification system,
and, DP: Dynamic positioning,
HCD: Human centred design,
HCI: Human-computer interaction,
LNG: Liquified natural gas,
LPG: Liquified petroleum gas

Fig.3 shows that simulators are not only used for mari- time education. Simulators are becoming more vital in industry processes such as de- sign and operations. Simulators are multidisciplinary labs that can gather expertise with a variety of roles for achieving specific purposes challenging the harsh and remote off- shore environment. The sixth category (Digital twins) is an emerging umbrella of ap- plications that naturally can be performed in a simulator. In Digital twins, the ships on the screens are representing real assets in operation. Simulators can be used to manage these assets, or as could be expected, to remotely control them.

One of the interviewees described the accuracy of physics in simulations as a challenge. Connecting this point with the aggregated range of applications. It is identified that some applications require higher functional fidelity than others. Functional fidelity represents the accuracy of the physics of ship movement in water (Hontvedt & Øvergård, 2020). For example, the application of training of nautical students probably requires a more relaxed functional fidelity than that of the application of pilot recruitment assessments. Such a challenge is raising awareness of the maritime simulator standard on accuracy requirements, which is elaborated in Section 4.3.

4.1 Simulator's Role in Our Lives

Simulators are no longer mainly used for nautical education. The offshore industries are rapidly growing with examples such as bottom-fixed wind turbines, floating wind farms, fish farming, subsea completions, bridges, tunnels, and the ocean surveying industry. Together with growth of the quantity and quality of offshore operations, the challenges imposed by distance-to-shore, environmental loads, weather, and the IMO energy efficiency regulations force the industry to evolve into a safer and more efficient one. Therefore, our methods for collaboration, design, and training have to evolve. There is a need for a development medium and simulators naturally fill this gap, and give us the potential to sit in the same room with our various roles from management, operations, nautical, designers and researchers.

In this sense, simulators can be viewed as enablers of operations that are usually deemed as impossible. We foresee that the demand for simulators will continue to rise.

Simulators will help us design and build the ships of tomorrow. They will help us remotely control surveying robots going as deep as the deepest point of the ocean goes. Simulators will help us enhance the way we install floating wind turbines. Simulators will help us enhance port infrastructure and waterways. They will help us in pilotage of huge containerships with autonomous tugboats. Simulators will train us to work together, with our different roles, different languages, and cultures. Likewise, simulators will help us manage our risks and achieve more with what we have.

4.2 Opportunities and Challenges

Simulators offer proof of concept capability to innovations in ship-bridge design, port design, and research ideas. Simulators are a haven for human factors and sociocultural diversity research. Nevertheless, the research and development of autonomous and remotely controlled vessels will depend largely on simulator experiments.

Main advantages of simulators are compressed into the following features: simulators enable human-in-the-loop and hardware-in-the-loop investigations. They allow investigations in harsh conditions, and in all kinds of weather, including winds, waves, and ocean currents. Simulators save time, they enable us to perform trials on a specific route relieving us from the duty of sailing back. Finally, simulators enable us to control variables, such as weather, that are impossible to control in real-world experiments.

Besides limitless opportunities, ship simulators have challenges of their own, some challenges are philosophical, linked to the fact that simulators *mimic* real-world, but they are not so. Other challenges are physical, related to the fact that ship simulators are not available upon demand, they are scarce and usually fully booked. The rest of the challenges are technological, even though advanced simulators provide a seamless performance that cannot be parted from reality, simulators do, occasionally, glitch, requiring updates and maintenance. In addition, the immersive feeling of a top notch navigation simulator does not imply realistic physics.

4.3 Simulator Accuracy Concerns

The broad scope of ship simulators' applications is raising the validity concern. In this paper, the concern is limited to hydrodynamic model fidelity that governs ship maneuvering behaviour in a simulator. Noting that most ship simulators included in this study are developed for education and training purposes, nevertheless, they are ac- tually used for a much wider application. In the maritime industry, ship models undergo subjective validations. Subjective testing is basically the acceptance of an experienced officer, which is an important consideration. However, the introduction of objective testing, in the certification of simulators and / or ship models is crucial. Objective testing is a quantitative assessment based on comparison with validation data. Validation data is derived from full-scale sea trials done with the specific ship the model is replicating, or from free-running basin trials (model tests).

The airline industry, according to the Certification Specifications for Aeroplane Flight Simulation Training Devices (CS-FSTD) of the European Aviation Safety Agency (EASA), is addressing accuracy concerns (CS-FSTD, 2018). The concerns are addressed within the certification specifications. Qualification guidelines include objective testing in addition to pilot acceptance (subjective testing) and functional testing. The objective testing covers a range of plane behaviour details including flight dynamics, the response of the aeroplane to drag, thrust, attitude, altitude, temperature, centre-of-gravity, and etc. Among others, test categories also cover ground effects, wind shear effects, simulator computer capacity, aerodynamic modelling, stall characteristics, icing, mass properties and others.

Taking the full flight simulators (FFS) as an example, they are classified in four levels, A, B, C, and D (level D has highest functionality) according to their functionalities and match against validation data given defined tolerances. The maritime industry should account for such certification specifications for ship models taking into consideration maneuvering behaviour in calm water and environmental effects.

In the maritime industry, a DNV Standard exists for Maritime Simulator Systems that gives requirements of the performance of maritime simulator systems. The objective of the standard is to provide appropriate levels of physics and behaviour realism in accordance with training and assessment objectives (DNVGL-ST-0033, 2017). The standard recognizes different types of simulators such as crisis management, oil spill, mobile offshore unit, high-speed craft, fishery and other simulator types, but does not provide certification specifications per type. Type specific requirements can be dealt with separately using compliance statements.

This standard lists requirements related to behavioural realism, physical realism, operating environment, and dynamic behaviour. Few of the general requirements specified therein relevant to ship dynamics are summarised as: Own ship shall be based on a 6 degree-of-freedom mathematical model. The model shall realistically simulate own ship hydrodynamics in open water conditions including effects of winds, waves, tidal stream and currents. Class A simulators, in addition, are required to simulate realistically own ship hydrodynamics in restricted waterways including shallow water effects, bank effects, interaction with other ships and direct, counter, and sheer currents.

An appendix is added to the standard version of 2017 for the documentation specifications of mathematical and hydrodynamic models used in simulator systems. This includes the documentation of speed data, tactical diameter, and crash stop distance. The mentioned data shall be modelled, documented and verified.

It is obvious that the standard aims to provide ‘fit-for-purpose’ simulators and touches upon ship behaviour and hydrodynamic modelling. Despite that, it is also observed that there are two main shortcomings of such a standard. First, the standard recognizes only education and training types of simulator applications. The other application categories, presented in fig. 3, are neglected. Second, the standard requires the verification of maneuverability indicators such as full speed and tactical diameter. This set of indicators is not elaborate enough to describe maneuverability of a ship and does not comply with the indicators specified in the maneuverability standards (IMO MSC.137(76), 2002). In addition, the standard does not specify how to verify the given indicators. The verification is indeed a challenge and it lies in the core of the matter of the objective of such a simulator standard: "providing appropriate level of physics and behaviour realism…"

4.4 Limitations

The three data collection methods used herein provide a solid base to answer the research questions, mainly on the application of simulators in the maritime industry. However, the used methods are not absolutely comprehensive in this endeavour reasons such as the following:

- The literature review provides insight about simulator application in the last 12 years, however, it is blind on the evolution of the use of simulators since they were first introduced in both academia and industry.
- Interviews may suffer from a selection bias because all the interviewees except one are from North-European countries. The representation of Asia, Africa, the Americas, and Australia is overlooked. In addition, other type of users exist that were not considered in the selection, such as nautical teachers and simulator developers.
- The case study provides a rich, relevant and up-to-date perspective that cannot be found in the literature, however, this is an eye-opener that there exist other perspectives not covered herein such as: Navy; Oil and gas industry and emerging blue economy industries.

4.5 Contribution

The combination of the three methods shows great potential in the use of simulators for both research and industry. The literature review provided examples from the research domain. The interviews provided deeper insight into experts' experiences, and the case study supplemented the results with relevant and up-to-date operational input. The primary contribution of this work is answering the research questions connected with the use, opportunities and challenges associated with maritime simulators. The primary contribution can be mainly manifested in the overview of application presented in **Fig. 3**.

The additional contribution is the identification of the accuracy concern. Some applications require high functional fidelity, meaning, high accuracy in ship dynamics during maneuvering. For example, assessment applications such as port studies, recruitment, and risk analysis. Outcomes of such simulator applications could drive decisions with considerable ramifications. In such cases, the simulator application could leap beyond the scope of its intended application. Raising an alarm on the ship dynamics fidelity, and after reviewing the maritime simulation standard, a gap in the requirements for ship dynamics evaluation was identified. A contrast is made with aeroplane simulator standards to confirm the relevance of the gap. This gap is clarified in Section 4.3.

5 Conclusions

5.1 Main findings

Ocean economy is addressing vital challenges such as food security, energy security and climate change. Emerging ocean operations face a multitude of challenges where simulators can serve as multidisciplinary laboratories for research, development, and innovation.

It is observed from the literature review that simulators invite researchers from various academic backgrounds, meaning that simulators are used for investigations concerning different perspectives such as human factors, development, training, learning and others. It is also observed that there is a lack of research contribution from the academic field of nautical science, probably because nautical students tend to fulfil the basic levels and proceed with operational careers instead of academic or research careers.

The interviewees agree on the potential simulators have in research, innovation and in changing industry workflows towards more inclusive design procedures and more collaborative operational mindsets.

Norwegian Coastal Administration Pilot Service uses ship simulators in recruitment, training, and innovation. Among other challenges, they face operational challenges, such as ships becoming larger, and waterways remain the same. They also have technological, interpersonal, fatigue-related, and practical challenges. NCA pilot service sees simulators as fit to contribute to training to the various kinds of challenges.

Simulators are used for applications beyond education and training. They are used for operator training, assessments, development and testing, and research and innovation. Some applications require higher fidelity in the ship dynamics than others. An accuracy concern in the maritime simulator standard is identified, raising awareness of the fitness of simulators for some of the high accuracy demanding applications.

5.2 Future work

- Develop a more comprehensive maritime simulator accuracy standard and specifications for validating simulators against these standards.

- Investigate the use of state-of-the-art Virtual Reality simulators in the maritime industry.

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Programming “The ordinary practice of seamen” into the AI-navigator: friendly and communicative interaction design between autonomous and manned vessels

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Abstract - This paper is aimed at programmers presently being recruited to code behaviour of a new type of automatic ships capable of navigating with an unmanned bridge. Today, navigation might be summarised as “the ordinary practice of seamen”, as the collision regulations expresses it. The day after tomorrow, when all ships are automatic, sea traffic management, electronically negotiated, will ensure traffic safety and efficiency. But the challenge will be tomorrow, when automatic ships will have to coexist with traditional manned navigation. To be understandable, the mathematical algorithms governing automated ships must mimic human navigation so that a bridge officer can “read” the autonomous ship’s actions. This paper will discuss some issues concerning communicative and friendly behaviour in navigation and how mathematical interpretations of the rules of the road and seamanship will be a challenge for this new field of research. How can we design automatic behaviour that will not only be safe, but also natural and understandable for humans on remaining conventional ships, fishing boats and small leisure crafts? Artificial intelligence has the potential to handle very complex scenarios and extrapolate them further into the future than the human brain can. The risk is that this might lead to automatic manoeuvring that are counterintuitive to mariners on conventional ships. To prevent this, automation must be designed in a transparent manner focusing on clarity. And here there might be a conflict with efficiency in the sense of shortest-route and fuel economy.

Keywords
Maritime Autonomous Surface Ships, MASS, interaction design, Human Factors, automation transparency.

Introduction

First, for non-mariners: Starboard side is the right side of a ship when facing forward. Consequently, the port side is to the left.

COLRREG is the rules of the road at sea, the acronym is short for “collision regulations” as expressed in the Convention on the *International Regulations for Preventing Collisions at Sea*. This convention has been adopted by the International Maritime Organization (IMO). It has been amended several times and the present version dated from 1972 (IMO, 1972). The COLREG is a thin booklet with 38 rules and some annexes that govern behaviour on international waters. National waters might have additional regulation but should not go against the COLREG.

COLREG lay the basis for interaction between ships at sea. The aim is safe and efficient sea traffic and constitute friendly and communicative behaviour among ships.

What is friendly and communicative interaction?

Just what is friendly and communicative interaction in ship navigation? A trivial example could be keeping well to the starboard side on a narrow channel leaving room for oncoming ships on your port side. This is of course in compliance with traffic regulations, COLREG, Rule 9. It is friendly because you are considering the spatial needs of oncoming and overtaking traffic. It is communicative because you signal with your position in the channel that you are leaving room for traffic and complying to a common set of rules which will, hopefully, make your further behaviour transparent. Another example could be using COLREG compliant light and sound signals to announce intended actions (e.g., one short blast/light flash: “I am altering my course to starboard” according to Rule 34). It is communicative by the very intention of the rule, and it is friendly because you show you care about interacting to create a safe and efficient traffic environment.

But you can be more or less friendly and more or less communicative while still complying to the COLREGs. Just like in road traffic a vehicle can be manoeuvred in a more or less aggressive manner. And economic efficiency has great influence on this.

What will change with the coming of MASS?

We are arguably at the dawn of a new era in shipping industry. The IMO is facilitating a new type of ship systems which are capable of navigation without human interference. They have called this ship system Maritime Autonomous Surface Ships, MASS for short (IMOb, 2021). MASS will supposedly be able to navigate automatically with the bridge unmanned part of the time or the whole time, presumably remotely monitored from a Remote Operation Centre with ability to remote control the ship, if needed. Unmanned automatic navigation has hitherto only been seen in small survey crafts or in military systems, but the aim of the MASS project is to introduce merchant ships both in inshore, coastal and ocean waters. If this introduction is successful, we might expect to see automatic and conventional manned ships interact in a new way.

Automation, autonomy, and artificial intelligence

Very briefly: *Automation* is the creation and application of technologies to produce and deliver goods and services with minimal human intervention. An *automaton* is a relatively self-operating machine, or control mechanism designed to automatically follow a sequence of operations or respond to predetermined instructions.

Already in the mid second century B.C., Ktesibios of Alexandria invented a water clock capable of regulating the waterflow as to keep a constant flow. By adapting to changes in the environment this self-controlling artifact changed the definition of what a machine cold do.

But if an artifact relies only on the prior knowledge of its designer, we can say it lacks *autonomy*. A rational agent is autonomous only if it can learn to compensate for partial and incorrect prior knowledge (Russel & Norvig, 2016). Hence the incorporation of *learning* is important to be successful.

This incorporation of what we call machine-learning allows an autonomous artifact to automatically learn and develop through experience without being explicitly programmed. This ability is part of what we call Artificial Intelligence (AI).

From this follows that by encountering different experiences two autonomous artifacts might behave differently although required to adhere to the same set of rules. In our case the artefacts are ships, autonomous agents in a complex traffic environment constructed by human experience and behaviour since centuries.

It is very doubtful that the IMO will ever accept two "AI-captains" that respond differently to the same situation depending on different experience through machine-learning (the way human captains do). Therefore, we can assume that the "autonomous" ships addressed in this paper could be better described as "automatic".

Maneuvering is an important means of communication.

Because COLREGS are based on traditional navigation, it is closely tied to human behaviour at sea as it has evolved during thousands of years. The second rule of COLREG explicitly points to the need to take "any precaution which may be required by the ordinary practice of seamen". For programmers coming from an entirely different domain, it will be a challenge to understand this practice.

Basic to all human interaction is communication. Interaction between ships at sea deals to a large extent with the problem of communicating intentions. Sometimes humans might have the same problem of collision avoidance e.g., when walking around in a crowded city environment: shall we meet to the right or the left of the pavement, how avoid bumping into each other crossing a crowded square? Although communication systems involving flag and semaphore systems, sound and light signals and in the last century voice over radio has been developed, manoeuvring remains the most readily used means of communicating intentions.
The example above of keeping to starboard in a narrow channel is obviously trivial, but it reflects the common practise of (most) seafarers as well as being part of the COLREGS.

Traffic separation might not be so difficult to achieve, using Traffic Separation Schemes (TSS), recommended routes and maybe exclusive MASS lanes. When the e-navigation feature of "route exchange" becomes reality and route intentions are routinely transmitted between ships, things might be easier (Porathe et. al, 2015). But until then collision avoidance will continue to be a challenge. So, how do we program automatic, human readable behaviour into a MASS?

A simple example of how COLREG compliant manoeuvrings can be more or less communicative could be an ordinary crossing situation with risk of collision (see Figure 1). In this a case, Rule 15 states that "the vessel which has the other on her starboard side shall keep out of the way and shall, if the circumstances of the case admit, avoid crossing ahead of the other vessel."

In Figure 1 you see two ships approaching each other on a collision course. The figure shows two alternative manoeuvrings, left top to bottom and right top to bottom. The staring situation (Frame 1, left and right) is the same for both scenarios.

First, ship A (own ship) has ship B on her starboard side and should give way according to the rule mentioned above. "Avoid crossing ahead of the other vessel" could be achieved in several ways: for example, by slowing down or turning to starboard, both actions result in passing behind the other ship. Turning starboard is the most common action as turning takes effect faster while slowing down will take longer time to take effect and be visible. The COLREGS further says that any action to avoid collision shall be made in “ample time”, be “substantial” and be done in “due regard to the observance of good seamanship” (Rule 8).

In Figure 1, frame two, two different give-way manoeuvres to starboard are illustrated. Both are done at the same “good” time, but the size of the course deviation is different (although the sketch is only schematic and compressed to save space).

Most efficient

In the left column ship A makes only a small course change to starboard (Figure 1, frame 2, left). The manoeuvre is based on a calculation of the precise course change needed to give way and go astern of ship B (assuming it is keeping course and speed, as prescribed in Rule 17) with a predefined CPA (Closest Point of Approach) behind vessel B. The precise CPA will depend on the context: on the open sea it might be 1 or 2 nautical miles, but in confined waters it might only be a few cables (1 cable = 0.1 nautical mile).

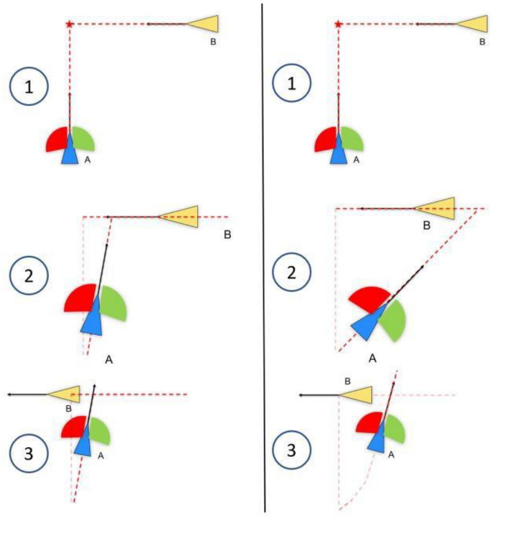

Figure 1. These two scenarios (left and right) show two different strategies for vessel A to give way for vessel B: In the left column a minimal course change is made to achieve the desired CPA, to the right a larger, less efficient but more “communicative” manoeuvre achieves the same CPA. (Illustration by the author).

Most communicative

In the right column, ship A makes a larger course change to starboard and shows her port side (red navigation light at night), and as the meeting proceeds, she turns slowly back to port, all the time with her heading pointing behind ship B, all the time showing her port side and red light, until she is back on her original course. Rule 8 says that an action shall be “substantial”, that “any alternation of course and/or speed to avoid collision shall, if the circumstances of the case admit, be large enough to be readily apparent to another vessel observing visually or by radar”.

If we compare these two strategies, we can see that the left strategy, route 2 in Figure 2, is the most efficient in terms of shortest sailing route (more fuel efficient), while the right strategy in Figure 1 (route 3 in Figure 2) is longer and thus less efficient in terms of time and energy consumption. (The difference in just one encounter is of course negatable but multiplied by a large number of ships each with a large number of encounters the cumulative effect will be substantial). Both strategies reach the same goal as seen from the perspective of ship A: avoiding collision by a COLREG compliant manoeuvre.

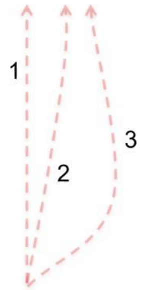

Figure 2. Route 1 lead to the collision so and we must choose between route 2 (more efficient but less communicative) or route 3 (more communicative but less efficient).

On the other hand, let us change perspective, and see the situation from the bridge of ship B, the right column manoeuvring strategy in Figure 1 resulting in route 3 in Figure 2. This manoeuvre is more salient and readable for a human navigator and thus preferable from a communication perspective. A human navigator on ship B will early see the intention of ship A, witch during the whole encounter shows it port side and red navigation light. In restricted visibility (addressed in Rule 19), when ships only see each other by radar, salient manoeuvring is even more important because it take some time for the automatic radar plotting to stabilise and show a targets course on the radar screen.

The dilemma for the programmer is some qualitative variables in the COLREGS:

1) When should the evasive manoeuvre commence? When is the "ample" and "good" time that Rule 8 talks about?
2) How large is a "substantial" a course change, which is among the actions that Rule 8 and 16 mention?
3) What is the CPA needed for a "safe passing distance" the other vessels?

Guidebooks used in maritime training can give some clues:

Ample time

What is the ample time to commence avoidance manoeuvres? When we talk about moving ships, time can also be translated to distance, and we can equally well ask: What the sufficient distance to commence avoidance manoeuvres? Cockcroft and Lameijer (1990) talks about "four stages in a collision situation" (p.129).

Stage 1. At a long range, before risk of collision exists, both vessels are free to take any action.

Stage 2. When the risk of collision first begins to apply, the give way vessel is required to take early and substantial action and the other vessel must keep her course and speed.

Stage 3. When it becomes apparent that the give-way vessel is not taking appropriate action, the stand-on vessel is *required* to give the whistle signal prescribed in Rule 34(d) (at least five short rapid blasts) and is *permitted* to take action to avoid collision by her action alone.

Stage 4. When collision cannot be avoided by the give-way vessel alone, the stand-on vessel is *required* to take such action as will best aid to avoid collision.

The crucial question is of course, the distance at which the various stages begin to apply? The unsatisfactory answer is "it depends". The distance will be greater for high-speed vessels that for vessels with slower speed. It will be longer for larger, less manoeuvrable vessels than for smaller. It will be greater in a less crowded traffic situation than in a crowded. It will be longer on the open sea than in confined waters. Cockcroft and Lameijer suggests that for a crossing situation in the open sea the outer limit for Stage 2, where a give-way manoeuvre begin, might be in the order of 5 to 8 nautical miles and the outer limits of Stage 3 would be about 2 to 3 miles (p. 130).

van Dokkum (2016) only writes that an action is made in ample time when there is time to spare for the other ship to react to a change of course and speed (pp. 47) there is no set moment when the obligation to give-way sets in.

Lee and Parker (2007) stress the need for early action. They quote a letter to the Nautical Institute where a captain writes "During my time in command I have noticed a deterioration in collision avoidance standards. I feel more threatened as ships seem to approach ever closer before giving way. The only solution I am left with is to assume that other ships will not obey the rules." (p. 155).

For instance, van Dokkum (2016) notes that during approach to a harbour it is not always possible to comply with the demands of in ample time and at a safe passing distance (p. 48).

A problem might be that a vessel, realizing that she is approaching a situation that might develop into a risk-of-collision situation, still considers herself being in what Cockcroft and Lameijer calls "Stage 1", at long range, before risk of collision exists, and therefore are free to take any action, while the other ship considers herself already being in "Stage 2" and manoeuvres according to COLREGS. The result might be one of confusion.

Lee and Parker (2007) remarks as a rule of thumb that 7.5 ship lengths can be a minimum distance for when an evasive 90 degree turn with 10-degree rudder must be started (p. 129).

Substantial action

As mentioned above COLREG Rule 8 states that "any alternation of course and/or speed to avoid collision shall [---] be large enough to be readily apparent to another vessel observing visually or by radar; a succession of small alternations of course and/or speed should be avoided," (IMO, 1972, p. 12) and in Rule 16, "Each vessel which is directed to keep out of the way of another vessel shall [---] take early and substantial action to keep well clear" (Ibid, p. 17).

For the size of a "substantial" course change Cockcroft and Lameijer (1990) suggests that a course change less than 10 degrees might be difficult to detect and hardly can be seen as "apparent", instead they recommend minimum 30 degrees course change, but preferable in the order of 60 to 90 degrees (p. 65).

van Dokkum (2016) states that a course alternation of at least 60 degrees is clearly visible (p. 83). He also mentions that the Dutch Council of Transport recommends that "showing your other side light when you give way makes it clear to the other vessel that you are giving way and prevents confusion" (p. 49).

Safe passing distance

COLREG Rule 8(d) states that "Action taken to avoid collision with another vessel shall be such as to result in passing at safe distance" (IMO, 1972, p. 12). This "safe passing distance" can be expressed in terms of Closest Point of Approach (CPA). Important to remember here is that there is a definite difference between a CPA in front of another vessel, called Bow Crossing Range (BCR) and passing behind a vessel's stern. When passing behind another ships stern the safe distance can be closer. Passing in front of another ship is not recommended, Rule 15 says "avoid crossing ahead of the other vessel" (Ibid, p. 17).

For the CPA, Lee and Parker (2007) recommend a safe passing distance of 2 nautical miles in open sea and 1 mile in restricted waters (p. 35). However, van Dokkum says that in narrow waters a passing distance of 0.1 nautical miles (behind a vessel) can be necessary (p. 47).

Safe passing distance (CPA) calculation thus needs to take into consideration sea room for manoeuvring (which is much less in confined waters than in open waters).

When demining the time or distance to where COLREG compliant behaviour should commence it might be useful to be aware of the concept of "ship safety zone" defined by IALA (2021) as "A zone around a vessel within which all other vessels should remain clear unless authorised". One may at the same time talk about a ship's "comfort zone" as being the zone around a ship which its watchstander wants clear of other ships. Such a comfort zone would be a psychological concept which will differ from navigator to navigator as well as with the context the ship is in. It should be possible to study the size of such "comfort zones" by processing AIS data – and such an exercise is recommended for the ambitious programmer. The result would probably be very different depending on the context ("it depends", see above), but also the *navigation culture* in a particular area. (What is normal behaviour in the Straits of Malacca?) I would imagine, that by doing such a study on what is "ample time" for a particular area and particular conditions, it could be possible to quantify the time or distance to when to commence some of the qualitative variables COLREG mentions. However, such quantification would only be valid during certain conditions.

The take-away is, that we will not be able to program a set distance for when a give-way ship should start its COLREG compliant manoeuvre, it will be dependent on a lot of contextual variables of which only some are mentioned above. A general advice to the automation programmer new to the maritime domain would be to carefully study maritime accident reports and listen to the discussion carried out by the commission regarding the causes of accidents. And most importantly, get your hands dirty, go onboard, sail and talk to the practitioners.

What will the introduction of MASS change?

Let us bring automatic collision avoidance and unmanned bridge into the simple crossing scenario above. Let us assume assume that the give-way ship (ship A in Figure 1) is navigating automatically. The programmers of the collision avoidance algorithm is faced with the dilemma of a more efficient or a more safe manoeuvre. Of course, COLREGS already talks about evasive manoeuvres bring "substantial" and made in "ample" time. But these entities are contextual and up to the programmer to define and quantify. The question is if salient and readable manoeuvring behaviour will come out on top when put against fuel efficiency and economy? Efficiency in terms of distance sailed and fuel spent (quantitative) might be easier to program than communicative, friendly, and salient behaviour (qualitative). Given that we here are discussing general behaviour for a potentially large number of future autonomous ships, there will be both economical as well as safety implication in the strategy we chose to program into our autonomous navigator.

Multi-ship encounters

In real life situations are mostly more complex than the two-ship encounter illustrated in the beginning of this paper. In reality an evasive manoeuvre for one ship may lead into risk of collision with other ships. Figure 3 illustrates such a complex situation in the English Channel. The black ship A is a ferry coming from Dunkirk destined for Dover. It is approaching the Dover Traffic Separation Scheme (TTS - purple border lines) which divides the English Channel into a south-westbound lane on the English side and a north-eastbound lane on the French side. The lanes have only one-way traffic, but crossing the TTS is allowed – "on a heading as nearly as practicable at right angles to the general direction of traffic flow" (COLREGS, Rule 10c). Sailing up the north-eastbound traffic lane is a number of ships. The blue ships have already passed ahead of the ferry, but the red ship is on collision course and the green ships might pose a problem later, depending on your actions. According to COLREGS all traffic in the north-eastbound lane must yield for the ferry, but the traffic in the south-westbound lane is stand-on in relation to the black ferry. How you deal with this situation if you were programming the collision avoidance algorithm for the black ferry A? Taking on the encounters in the north-eastbound traffic lane

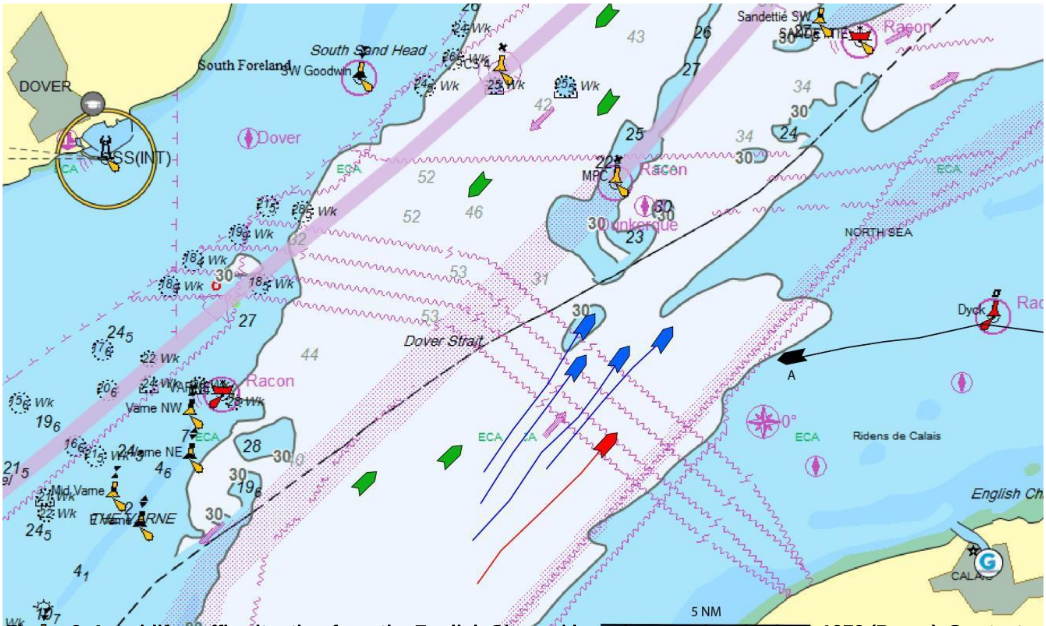

Figure 3. A real-life traffic situation from the English Channel based on a radar plot from 1979 (Bruce). See text for details.

relying on your right of way, could be one strategy, but for the oncoming ships in the south-westbound lane you are the give-way ship.

Take a look at the real-time traffic in the Dover Strait on e.g. MarineTraffic.com. It varies from time to time but for a ferry crossing the Channel it will most often most often be a complex situation. And a general consideration is if you should take encounters "one-by-one", or if you should try and see the bigger picture and set up a more wholistic strategy for the crossing.

The particular situation depicted in Figure 3 are based of an accident that happened in 1979. The black ferry A is the French train ferry Saint-Germain and the red ship is the bulk carrier Artadi. This accident happened in dark and foggy conditions at 4 o'clock in the morning. The black, red and blue ships' positions are all collected from a radar plot submitted by the H.M. Coast Guard at St. Margaret's Bay, Kent, England, and depicts these ships position at 03:52, about 10 minutes before the collision between Saint-Germain and Artadi. All the green ships in the area outside of the radar plot submitted to the accident commission have been added by the author to add to the realism of the scenario. In the following we shall se the choices made by the captains of Saint-Germain and Artadi, as described in the accident report (Bruce, 1979).

The captain on Saint Germain did not want to push his way over the north-eastbound traffic lane. His intention was instead to turn port outside of the of following southwest along outside the border of the TSS, and proceed south-west in the unregulated area outside the TSS until the traffic situation had eased and he could cross the TSS in a right angle according to Rule 10c. The captain on Sain-Germain started to turn port a 03:55.

Onboard the Artadi, the French pilot and the captain had rightly assumed that the radar echo was the ferry for Dover. The assumed she was going to cross diagonally over the TSS and coming from starboard she was the stand-on vessel and should keep her course and speed. So Artadi started a starboard turn at 03:55 precisely at the same time as the Saint-Germain started her turn. They collided some 5 minutes later resulting in the loss of two lives.

Strategies of human and automatic decision-making

The human brain has a limited capacity. A simple example proposed by Miller (1956) suggests that a human only can keep 7 plus/minus 2 "chunks" of information in her short-term memory at any time, and only a limited number of options in a decision-making situation. With the much-extended "brain" capacity, a computer-based automation system could actively hold much more information and compare many more options without confirmation bias and emotional shortcomings well known to human decision-making, and as such plan an efficient route through a complex traffic situation, taking many more factors into consideration, than a human could.

To get an example of human behaviour in such situations, I spoke some years ago with a bridge officer with long experience from car carriers on the Far East-Europe route. When we talked about how to handle the dense traffic situation in the Singapore and Malacca Straits, he said "You cannot really plan ahead, you just need to stick your bow in there and then take each encounter as it comes" (Porathe, personal communication). This is the "opportunistic" way we avoid bumping into one another when walking on a crowded sidewalk.

The captain on the ferry the Saint-Germain, however, tried a more wholistic strategy when he choice to postpone the crossing until the traffic had cleared, unfortunately he did not communicate this intention to the Artade.

Accidents in the maritime domain has been greatly reduced by Traffic Separation Schemes although the story with Saint-Germain and Artade suggests something else. When the Dover Strait TSS was introduced in 1967 the number of accidents diminishes significantly (IMO, n.d.). This suggests that traffic organization have effect on the number of accidents.

In a future scenario with Sea Traffic Management organizing automatic ships on pre-planned routes contiguously communicating delays and other changes, the potential is that we will have safer shipping. For the present, the challenge is to introduce MASS into a conventional human-centred traffic paradigm, with a mismatch between the human and the automatic navigator. In such cases maybe smart and efficient but less understandable, actions suggested by the automation must be sacrificed for less efficient but more understandable manoeuvres? Or should we acknowledge that automatically navigated ships will behave in a somewhat "different" manner and that we instead need to flag them up, so that they become visible for manned ships in the vicinity?

Communicating "autonomous mode"

Given that ships navigating in autonomous mode, using mathematical algorithms might come up with surprising manoeuvring solutions, it could be useful to mark those ships in a way that makes them identifiable. For future MASS it could be evident from their design that they are unmanned and thus automatic, but for a long time one might assume that many ships will be IMO "degree one" ships: "Ship with automated processes and decision support: Seafarers are on board to operate and control shipboard systems and functions. Some operations may be automated and at times be unsupervised but with seafarers on board ready to take control." (IMOa, 2021).

The gradual introduction of increased automation is also supported by real-world projects, such as ASKO and Yara Birkeland in Norway which in the beginning will run in combined human/automatic mode. The next step will be unmanned (remote operated), and final step (if achieved) full automation mode (autonomous).

When such ships are navigating automated and unsupervised, the ship could display some sort of "MASS signal" making its navigation mode salient. For instance, in the ECDIS an added letter "A" (for "autonomous") could be added to the ship symbol (see Figure 4), and in the physical domain, e.g., a *turquoise* all-round light could be carried in the masthead. In the automotive industry self-driving cars cause some concern when it comes to interaction with other road users, both conventional vehicles and pedestrians. A growing research field are examining whether self-driving vehicles should be equipped with an external Human-Machine Interface (eHMI) to facilitate interactions with human road users. Werner (2018) has studied use of light signals for self-driving cars and is suggesting using a turquoise colour for cars. Cars has to some extent the same light environment as ships where green and red lights are important information carriers. A new light signal must be clearly distinguishable and must not be confused with ship's navigation lights and lighthouses.

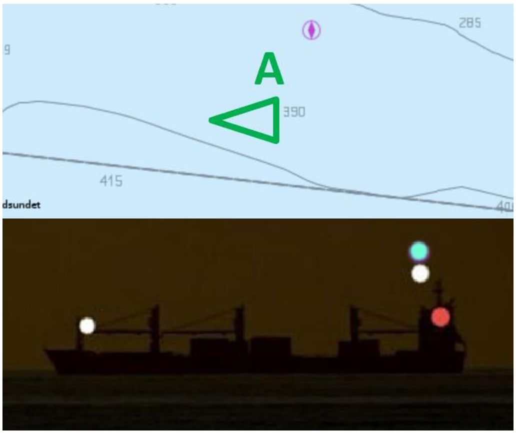

Figure 4. To distinguish ships navigating in an "automates and unsupervised" mode a designated letter (e.g. "A") could be added to their AIS symbol and a turquoise all-round masthead light could be used.

According to Faas, et al. (2018) the development of standards for eHMI design is in process by the standardization associations Society of Automotive Engineers (SAE International - "Automated Driving

System (ADS) Marker Lamp" - J3134), United Nations Economic Commission for Europe (UNECE - taskforce "Autonomous Vehicle Signalling Requirements" - AVSR). The International Organization for Standardization (ISO, 2018) published the "ISO/TR 23049:2018 Road Vehicles – Ergonomic aspects of external visual communication from automated vehicles to other road users", concluding that an appropriate eHMI design cannot be defined yet. Up to now, there is no agreement on the design guidelines for eHMI lamps.

Some projects are presently looking into the use of turquoise as a designated light colour for self-driving cars (Faas, et al., 2018).

A similar approach should be used for the maritime domain giving it the benefit of a standardised light signal for vessels with "automated behaviour".

VHF communication

If a ships manoeuvring is unclear, a last resort for the bridge officer is to grab the VHF radio handset and ask for her intentions. Traditionally ships communicate using voice over VHF radio. The Automatic Identification System (AIS) revolutionised ship communication in 2002 by making it possible to see the names and call signs of ships in the vicinity directly on the ECDIS screen. Thus, ship could be called by name instead of calling e.g. "ship on my starboard side" which had to be used earlier and which sometimes lead to misunderstandings. Due to a limited the number of VHF channels and an increased density of ships it can in some areas become a quite irritating sound environment on the bridge with many ships calling on two or three radio channels simultaneously. Sometimes you might need to stand in line and wait for an opening to make a call. A voice radio call made to a unmanned MASS will be redirected to a shore Remote Operations Centre (ROC) where a human operator will answer. However, this operator might need some time to get into the loop or might be busy supervising another MASS under his responsibility. To minimize the need for asking for intentions a MASS should be as transparent as technically possible with its intentions.

Potentially, VHF voice communication with an automated vessel could be automized. E.g., when intentions of a vessel are called upon, a RPA (robot) could read out the present intentions of the vessel (e.g. keeping course or altering course to …).

Communicating intentions though AIS

In many e-Navigation projects during the last decade *route exchange* and sharing of intentions has been discussed and prototyped (e.g. EfficienSea, MONALISA, ACCSEAS). The concept has been that a ship sends out a number of waypoints ahead of its present position, from its voyage plan though the AIS system. By right-clicking any such ship in the ECDIS and selecting "Show intentions" the ship's immideate route legs will be shown. Ships routeing can for the navigation planner be simplified by the use of "reference routes" presently beeing rolled out by many autorities (e.g. Norway, Sweden, Australia). In Norway reference routes can be found on routinfo.no, some of them being traffic separated (dual lane). An extended suggesion is to make "moving havens" to show not only the intended route but also the precice location of a ship that is part of a ship traffic coordination system. The details of these features are out of the scope of this paper but a summary and further references can be found in e.g. Porathe, et al., 2015 and Porathe, 2020.

Conclusions

In a future traffic situation where all ships are autonomous, where the traffic is coordinated and where MASS necosiate electronically for situations not covered by the traffic managent, we can assume that the safety will be high. But as long at MASS needs to interact with traditional manned vessels, their behaviour needs to be understood on the bridge of manned ships. The risk is that automatic manoeuvring characteristics will strive for efficiency rather than clarity and safety. Human Factors research and input from active seafarers will be crucial in the development and testing of autonomous navigation.

This paper has suggested a concept of "friendly and communicative" behavior as a leading star for the development of this maneuvering characteristic. Some examples of what "friendly and communicative" might mean has also been given. The concluding point here is that the programmers of future MASS navigation behavior must work in CLOSE cooperation with the maritime community. One would think this should be self-evident, but reality has again and again shown that this is often not praxis.

Acknowledgements

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Designing for trustworthiness, training for trust. An overview of trust issues in human autonomy collaboration in maritime context

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Abstract - Background: Trust is recognised as a highly relevant issue for autonomous maritime operations. Increased agency of intelligent technologies enables interactions with humans to be bilateral, context-dependent and in result, more social. Research suggests that human autonomy teaming is a subject to similar psychological mechanisms as teaming between human actors.

Research interest: Our study aims to identify trust issues linked to autonomous maritime operations and connect them with the existing concepts of trust and trustworthiness.

Method: Qualitative analysis of group interviews and data-driven literature review.

Results: The Human Autonomy Enable (HUMANE) workshops identified four meta-categories of trust issues, including operational trust, trustworthiness, organisational trust and social acceptance. Each category of trust issues is linked to existing concepts. The results point towards areas for improvement in maritime design and training: measuring perceived autonomy, application of explainable artificial intelligence, exploring linguistic and cultural aspects of communication, facilitating calibration of trust, supporting cooperation in instant teams, and responsible promoting of social acceptance.

Keywords
Ergoship 2021, maritime Human Factors, autonomous maritime operations, MASS, trust, trustworthiness, human autonomy teaming.

Introduction

The perspective of introducing autonomous maritime operations brings up a range of challenging questions regarding the human role in the sociotechnical system. In the regulatory scoping exercise, the International Maritime Organisation differentiated between four degrees of autonomy, including automated processes and decision support for seafarers (degree one), remote control of a ship with seafarers onboard (degree two), remote control of an unmanned ship (degree three) and a fully autonomous ship (degree four) (IMO, 2021). At least in the first three degrees of autonomy suggest that humas maintain their key role in decision making. The fourth degree of autonomy is defined by the ability of an operating system to make decisions by itself, without human intervention. However, the degree of autonomy of a ship could change depending on conditions. The same vessel could operate as fully autonomous, but under certain conditions be controlled by an operator on board or on shore. Introducing autonomous operations, independently of the degree, implies changes to the existing roles of maritime personnel.

The IMO distinction includes automation, remoting and autonomy under a joint term autonomy. In this paper, we separate automation from intelligent technologies that are considered disruptive for the maritime industry. This separation is useful from Human Factors perspective because human-autonomy interactions are expected to be different than those between human and automation. Automation is an "execution of machine function that was previously carried out by a human" (Parasuraman & Riley, 1997, p. 231). To refer to autonomy, we use the umbrella term Robotic, Intelligent, Autonomous (RIA) technology, coined by the International Organization for Standardization (ISO). ISO uses the term RIA to describe different forms of technology with an ability to self-regulate and self-govern (ISO, 2021). These characteristics allow bilateral, context-dependent and, in result, social communication between RIA and humans. While automation is a tool for replacing human work, RIA can be viewed as something more – even as an assistant or a teammate. Therefore, trust appears to be even more relevant aspect of interaction between humans and technology.

Introducing RIA to a sociotechnical system increases complexity by bringing in more interfaces, more information, and more interconnections. Dealing with this complexity remains in the human realm of responsibility. RIA systems can thrive in limited contexts, for example, within the structured environment of a factory. On the other hand, in complex, unpredictable environments, cooperation between humans and RIA can be more beneficial than using RIA alone (Kazerooni, 2005).

ISO (2021) offers an open list of design paradigms for human RIA relationships, including augmentation of human capabilities, remoting, replacement, teaming, or symbiosis. Among these paradigms teaming appears to receive the most attention from the Human Factors community (McNeese, Demir, Cooke, & Myers, 2018; Shively et al., 2017). Discussing autonomous maritime operations from the perspective of human RIA relationships helps overcome some of the weaknesses of the concept of levels (or degrees) of autonomy pointed out by Endsley (2018): lack of distinction between automation and autonomy and insufficient consideration of dynamic changes in operation modes.

Designing sociotechnical systems where RIA and humans cooperate requires Human Factors considerations on multiple levels: effects on individuals, teams, organisations and, in a larger scale, on society (ISO, 2021). Trust related issues can also be approached from this multiple-level perspective. In order to achieve that insight, there is a need for conceptual framework, or possibly many frameworks that can capture trust and address possible issues that emerge from humans RIA collaboration.

This paper explores trust as an element of cooperation between humans and RIA on multiple levels, connecting findings from the HUMANE research project with existing knowledge about trust. Current conceptualisations come from applications of RIA technologies in other industries and focus especially human autonomy teaming (HAT). Trust is identified as an urgent issue for enabling autonomous maritime operations (Mallam, Nazir, Sharma, & Veie, 2018) and a key concern for remote operations and public acceptance of autonomous vessels (Lutzhoft, Hynnekleiv, Earthy, & Petersen, 2019). In this paper, we explore trust-related concepts relevant for autonomous maritime operations.

Methods

The Human Maritime Autonomy Enable (HUMANE) research project evaluates the implications of maritime autonomy from a human-centred perspective. The primary method of data collection is workshops that involve experts with work experience in the maritime domain and expertise connected to autonomous maritime operations. Workshops 1.-3. were organised in a focus group style and workshop 4. took place as a series of individual interviews (see Table 1.)

The workshop participants represented shipping companies, classification societies, technology manufacturers, ship owners, communication companies, crew management companies, government agencies, insurance and law companies, research organisations and academia (see Table 2.). In total, the study includes data collected from 70 experts.

Table 1. HUMANE expert workshops

1.	System safety & cyber security	October 2018
2.	Legal implications	January 2019
3.	Skill sets, competence and knowledge	November 2019
4.	Organisational & job design issues	March-June 2021

Table 2. Organisations represented by the HUMANE workshop participants.

CIRM	SINTEF	Inmarsat
Massterly	BW Gas	Wärtsilä
Rolls Royce	Bellona	MTI-NYK
DNV-GL	Lloyd's Register	Wilhelmsen Ship Management
InterManager	ABB	Norcontrol
Kongsberg Maritime	Kongsberg Seatex	Maritime Robotics
F-Secure	RISE Viktoria	EXMAR
Norwegian Maritime Authority	Norwegian Coastal Administration	Swedish Transport Agency
European Maritime Safety Agency	Danish Maritime Authority	International Marine Contractors Association
IMarEST's Maritime Autonomous Surface Ships Special Interest Group	The International Transport Workers' Federation	BIMCO
Safe Marine	Gard	Møkster
InterManager	BW Offshore	Solstad Offshore
SIMAC	SIMSEA	BMT Global
SeaBot XR	Aboa Mare Maritime Academy and Training Center	University of Gothenburg
Norwegian University of Science and Technology	University of South-Eastern Norway	Western Norway University of Applied Sciences
National Maritime College of Ireland	University of Southampton	Åbo Akademi University

During the workshops, the participants received a set of questions related to the workshop's themes. The discussions were audio-recorded and transcribed.

The research procedure did not involve direct questions or regarding trust. However, the qualitative analysis of the data revealed trust as a reoccurring theme during all the HUMANE workshops.

The result section includes a selection of quotes that guide the search for existing theoretical frameworks and the discussion of their relevance for maritime settings.

Background

Trust is a concept discussed over many disciplines, especially psychology, sociology, political science, and economics. Multiple definitions of trust and related concepts can be found, including distinction between trust and trustworthiness. Bauer (2017) points out that the boundary between trust and trustworthiness in literature is often blurred and ill-defined. Especially in political science and sociology, trustworthiness is often considered a synonym for trust. Colquitt, Scott, and LePine (2007), in their meta-analysis linking trust with job performance and risk taking refer to trust as "the intention to accept vulnerability to a trustee based on positive expectations of his or her actions" while trustworthiness is defined by them as "the ability, benevolence, and integrity of a trustee" (Colquitt et al., 2007, p. 909). Trust is therefore a characteristic of a trustor and trustworthiness is a characteristic a trustee. Translating this distinction to human RIA collaboration, trust would be an intention to accept vulnerability to RIA based on positive expectation of its performance. Trustworthiness could be then defined as reliability of RIA technology.

Conceptualisations of trust in an interpersonal context include single- and multidimensional models explaining psychological mechanisms of trust between humans. There are examples of a successful application of single-dimensional theories in technology-related domains, such as assessing IT acceptance (Gefen, 2002). Mayer, Davis, & Schoorman (1995) created a multidimensional model of organisational trust, including three components: *integrity, benevolence,* and *ability.*

Integrity refers to the "trustor's perception that the trustee adheres to a set of principles that the trustor finds acceptable" (Mayer et al., 1995, p. 719) and has links to honesty and morality. This dimension can be used to describe RIA as long as it is designed to communicate in a social manner and to follow moral rules.

Benevolence is "the extent to which a trustee is believed to want to do good to the trustor, aside from an egocentric profit motive" (Mayer et al., 1995, p. 718). In other words, it is a perception of a positive attitude of the trustee towards the trustor. This can be extended to the entity behind RIA technology, especially the ethical aspects of processing the data. One of many concerns connected to disruptive technology is that in long term it will replace humans (Nautilius, 2018).

Lastly, the multidimensional model of organisational trust includes *ability* - "that group of skills, competencies, and characteristics that enable a party to have influence within some specific domain" (Mayer et al., 1995, p. 717). A meta-analysis performed by Colquitt et al. (2007) suggests that all three trust antecedents: integrity, benevolence, and ability, have unique and significant links to trust.

Kox, Kerstholt, Barnhoorn, and Eikelboom (2019) utilised the multidimensional model of trust in an experiment where a human participant interacted with a virtual teammate, which was either a human or a robot. The study indicated that the type of teammate (human/robot) did not affect the level of perceived trust. The experiment's outcome suggests that teaming human-human and human-autonomy are subjects to similar psychological and social mechanisms.

There remains a question whether the knowledge about interpersonal trust can be utilised in research and practice for enabling collaboration between humans and RIA, especially in the maritime domain.

Results

A set of trust-related themes emerge from the qualitative analysis. The themes are grouped into four categories: trust as technology acceptance, organisational trust, operational trust, and trustworthiness (see Figure 1.). These categories reach beyond the interpersonal level, or in case of human RIA collaboration, beyond the level of interaction between human and technology.

The categories that appeared in the data correspond with categories of human-RIA issues described by ISO (ISO, 2021) (see Figure 2.) Operational trust and trustworthiness belong to issues on the level of effects of humans and human-RIA interactions. Organisational trust connects a sociotechnical system and its organisational context, including elements such as forming instant teams and leadership, but also organisation’s policy and ethics. Finally, technology acceptance covers all the levels of issues, starting from affecting technology users to the society at large.

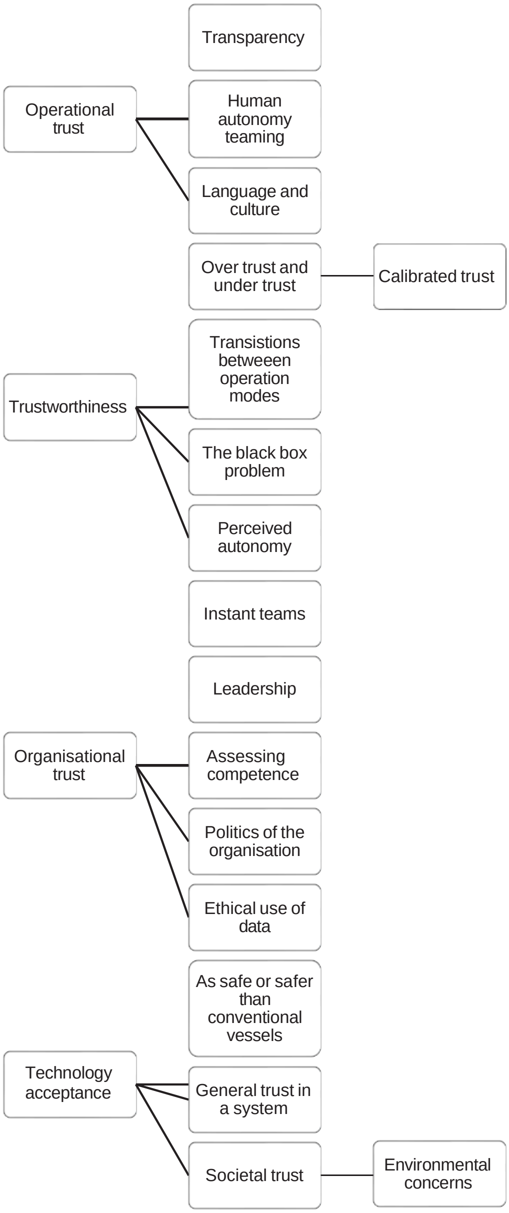

Figure 1. Trust-related themes identified in the thematic analysis of the data.

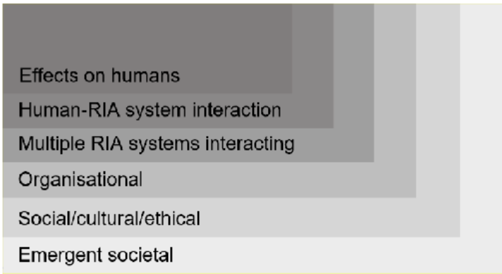

Figure 2. Categories of human-RIA issues. Adapted from *Ergonomics — Ergonomics of human/system interaction — Part 810: Human/system issues of robotic, intelligent and autonomous systems,* by ISO/CD TR 9241-810.

Operational trust

"There is another dynamic into this, and that's trust. How can seafarers trust the information they receive?"

"It's relatively easy to build a fully manual ship or a fully autonomous. If you have to have man and machine with human in the loop, that's difficult."

"There are still a couple of things that we need to work out. The first is how to transfer information from the machine to humans and from human to machines (...) How do we ensure that we have the proper level of expectation management on both sides so that the machine understands what the human is capable and not capable of and vice versa also?"

"One more was adaptive automation skills, the idea that you are not working with one level of automation, that it varies. And knowing how to team with an adaptive automation system. So, for example, when docking, it is more manual and hands-on, but when transiting, it is more towards autopilot and how to constantly be in the loop during various levels of automation."

"And how do they trust the system when they switch between these levels? So do you trust the systems? Because you need to trust the systems if you are handing it over to automation. You are going to need the skills (...)"

"How will it affect us or the person in that role in terms of being able to be on the line as both trusting the system and having its passivity and in terms of being on a monitoring function and all that framework would include"

Trust is discussed in an operational context as a variable influencing decision making and the ability of a system to stay in control. For the operator and RIA to be able to work together towards a common goal, the operator needs to understand a system's current state and predict future behaviour under current circumstances. What is more, RIA needs to understand the operator; hence, the operators' behaviour needs to be designed into the system. This additional loop makes the human-machine interaction different from using 'ordinary' automation, which does not have the capacity to self-govern or to sense needs of an operator.

Switching between autonomy levels and handovers were discussed by the participants as a challenge that specific for autonomous maritime operations. The themes that emerged were generalised trust in ‘in the system’ working as a whole, not only as separate components. This connects to already existing challenge in the maritime industry, namely the integration of technological systems. Comments also highlighted the importance of RIA’s transparency.

"Humans need to understand what the machine is doing. The machine has to show what it is going to do."

"(...) the end user wanted information about how a particular algorithm worked and needed it explained in a way that operators would understand so that they would trust that the algorithm was giving them accurate and actionable information (...) "

"The computer has to do what the second officer has to do, explain to the guy coming up, this is the situation, this is what I have observed, this is the problem I have, please tell me, I can't handle this myself. "

ISO (2021) defines teaming as humans and RIA working together for a common goal. The standard also specifies that for effective teaming, RIA must follow the rules of social interaction. Therefore, the communication between humans and autonomy should be bilateral and performed with the use of a code that can be understood by both parties.

Research conducted by Merritt and Ilgen (2008) suggests that trust in an automated system begins with dispositional trust of an individual and later develops as history-based trust connected to experience with this particular piece of technology. Understanding regular automation is challenging enough for humans (Hollnagel & Woods, 2005).

When technology is self-governing according to a perpetually changing situation, the RIA must communicate and make itself understandable and transparent to a human operator. Understanding RIA connects to the concept of explainable artificial intelligence, which is "a set of processes and methods that allows human users to comprehend and trust the results and output created by machine learning algorithms" ("Explainable AI", 2021). Research in robotics shows how explanations impact human trust, which in turn decides reliance and use of robots (Dziandolet et al., 2003).

"The machine could be speaking English. I could be speaking Chinese and it comes out the same. (…) I agree there has to be commonality, but how that’s achieved is a different question."

"How will it affect the trust from a human perspective that if I’m speaking to a machine in Urdu and the machine is replying in translate?"

The participants signalled the cultural and linguistic dimensions of communication between RIA and humans. The comments revealed the underlying assumption that RIA communicating in the native language of the operator would have a positive effect on trust. Also, there is a question whether automatic translation affects trust.

Trustworthiness

"That's very human thing. If it looks trustworthy, we will trust it. That is not a human fault. That is probably a system fault. Looking too good, too intelligent."

Translating the division between trust and trustworthiness known from interpersonal literature to human RIA collaboration, trust is a human attribute. It is an intention to accept vulnerability based on positive expectations of technology performance. Trustworthiness is the property of technology and is a concept very close to reliability.

One might expect that in ideal settings, human trust is directly linked to the trustworthiness of a particular piece of intelligent technology. However, the relationship between trustworthiness and trust is not always congruent. The possible moderators can be found both on the technology side and the operator side. Is the trustworthiness connected to what the RIA presents to the operator - how does it look, and how does it communicate? Does RIA look intelligent, advanced, reliable? Does it communicate in terms of presenting facts and certainty levels or more direct recommendations for the operator? Possible moderators of trust and trustworthiness relationship on the operator's level could be previous experiences with this or similar technology, level of understanding the mechanisms, confidence in hers or his own professional skills, personal values, culture and so forth. Research conducted by Merritt and Ilgen (2008) suggests that trust in an automated system begins with the dispositional trust of an individual and later develops as history-based trust connected to experience with this piece of technology.

"That's very human thing. If it looks trustworthy, we will trust it. That is not a human fault. That is probably a system fault. Looking too good, too intelligent."

Advertising technology as innovative and autonomous can lead to a situation where the perceived autonomy of RIA is higher than its actual capabilities. ISO (2021) points out that "a result behaviour that is perceived by a user as autonomous is a more common phenomenon than an autonomous agent" (ISO, 2021, p. 5). This effect was described much earlier by Woods (1996). The author points out that automation is often seen as autonomous (even when it is not), which alters the team composition. The new, advanced piece of technology becomes an agent or a teammate. What is more, when complex technologies with high autonomy are combined with insufficient feedback for the user, they can be viewed as agents independent of the operator (perceived animacy) (Woods, 1996). Therefore, the degree to which RIA system behaviour is perceived as autonomous is an important measure that should be addressed in the design process.

"And then you got this human trust, over-trust, under-trust problems..."

"A lot of seafarers trusted a defective GPS then they trusted their own skills to handle the ship manually (...) so not over trusting the system is is equally important as it has always been but it might be more stressed when it comes to even more fancy, flashy systems that look very cool and very smart."

"The issue of trust in automation arose because the technology didn't provide enough information to operators that a particular job or task was in process or being worked on, which led to a lot of repetition in tasks and general frustration that it wasn't working."

"I've been on a ship not very long ago where (...) they've got a fully functioning or supposedly fully functioning automation system. They never switch it on because they don't trust it. Because they believe it wasn't properly wired when it came out of the yard."

ISO (2021) points to potential hazards if Human Factors principles are not applied to designing RIA systems. One of them is the inappropriate levels of trust in the system, namely under-trust or over-trust. Under-trust would result in unwillingness to operate the system, only fragmentary use of the RIA's functions and consequently not integrating the RIA into the larger system, as well as increased workload due to excessive supervisory actions. Over-trust, on the other hand, could result in the operator being disengaged with the task, staying out of the loop, and becoming complacent.

In the over-trust and under-trust approach, trust is seen as a continuum. The preferred values of trust would be situated in the middle of this continuum. However, such an approach brings challenges in defining the optimal level of trust.

Calibrated trust is a positive representation of the under-trust and over-trust continuum presented in the section above. Fallon, Murphy, Zimmerman, and Mueller (2010) view the calibration of trust as a process of sensemaking. Sensemaking is defined as "a deliberate process that decision makers rely on to improve their awareness of uncertain and ambiguous situations" (Fallon et al., 2010, p. 3). In this case, the RIA's behaviour is uncertain and ambiguous. The operator, by interacting with RIA, actively makes sense of its functioning and identifies possible weaknesses and performance under different circumstances. We suggest that calibration of trust can be achieved by promoting sensemaking through design as well as offering familiarisation with RIA in different settings. Such training would allow developing a mental model of how RIA operates. However, it is important to note that the process of sensemaking is cognitively challenging and time-consuming. This should be taken into account when introducing RIA and designing training programmes for maritime personnel.

Calibration of trust is recognised by Sanneman and Shah (2020) as critical for human RIA teaming, and is supported by providing explanations about RIA’s purpose, process, and performance. The authors recommend that the impact of explanations on human trust should be measured using a trust scale and behavioural metric, such as reliance or compliance.

Organisational trust

"Political stress. I think is a major one. Internally, it is a major problem. And that sounds strange, but I genuinely believe one of the biggest problems our masters and chief engineers have is working their way through the politics of the organisation. They spend more time doing that than they do driving ships."

The participants discussed the problem of 'political stress' understood as ambiguous and tacit rules of the organisation that influence and obstruct decision making onboard. This theme connects to organisational trust components: integrity, reliability an openness, that influence safety-related actions like whistleblowing (Binikos, 2008). Tsspecific for maritime industry, s Organisational trust is felt by an individual comparably to interpersonal trust, however the mechanisms of forming and maintaining trust may differ (Luoma-aho et al., 2012).

Trust was discussed as a current issue in the maritime industry, independent of technological change. However, the introduction of RIA is expected to have effects also on organisational level. A study of AI-driven services showed that building trust in technology requires organisational efforts and increased visibility of management, especially in cases of low transparency of AI decision making. (Pan, Chakkol, & Selviaridis, 2020). It seems that transparency and trust within organisation structure can produce positive outcomes on the quality of human RIA collaboration.

"(...) organisational design is a major issue which is not being managed. (...) thinking about what is leadership about? What is people management about? What do we actually want at the end of the day? Do we want the bosses controlling him and her or do we empower them to get on with their job and trust them and provide the skill set for them so that they can be effective? We make sure we pick the right person to go into the place, the job, in the first place."

The participants also mentioned leadership as one of the components of organisational design that need to be addressed in the context of autonomous maritime operations. The comment touched upon hierarchy and a choice between directive or empowering leadership. In research, leadership relationship was identified as a mediator of organisational trust (Pucetaite, Novelskaite, & Markunaite, 2015).

"They are still teaching the students celestial navigation (...) I don't think that they will get proficient enough to actually do it. But yeah, and they have to know everything you in case of a system failure. So they are kind of training that students to be backup for the technology."

"One of the big trends in the oil and gas industry is verification of competence. (...) in order to operate, you have to prove that you're competent (...) there's a complete lack of trust in the people's ability."

"It's (...) always problematic to assess competence. And, the major solution is to reduce the subjective impact of the instructor (...) I think that it's a matter of trust between humans and technologies."

Another reoccurring theme during the HUMANE workshops was competence assessment. The competence of maritime personnel is expected to increase in connection to autonomous operations. Trust in competence is recognised as a determinant of the effectiveness of risk communication (Twyman, Harvey, & Harries, 2008).

Instant teams

"I have (...) issue that is about trust. How do you build up trust between these guys if they are not teams? It's just the guy on the call, it's like calling 911"

Autonomous maritime operations, especially remote will increase the human interactions occurring in physical distance, possibly assisted, or facilitated by RIA. Studies of teamwork between human actors in the maritime traffic system, such as masters, pilots and VTS operators suggest there is room for improvement (Mansson, Lutzhoft, & Brooks, 2017). The main challenge for these maritime professionals is establishing common ground, which is essential for coordination. When engaging in teamwork, efforts are focused on adaptations that go beyond procedures and prescribed roles, Collaboration within instant teams formed between human actors is a situation with high uncertainty and time limitations. There is no opportunity for developing trust based on experience. While forming instant teams between human actors requires more consideration, research interest is also needed for exploring design approaches for adding RIA to the instant team equation.

Trust as social acceptance

"(...) and how can the public at large trust how things are going, as they should?"

"(...) society at large needs to trust that these systems are functional and that we can actually do them and use them."

"(...) we are supposed to have a system in place that generates trust."

"You need to have it being a little bit safer. As safe as is kind of the thing. "

"(...) it is trust for the people that operate the ships, but it is also the trust of society in general that the safety of people and certainly the environment these days is being looked after on their behalf."

"It could possibly be because the technology is there, kind of, but we have some way to go for the social acceptance and for other different kinds of things as well."

"It is a wider question for society as a whole because it is the same with cars and the same with aircraft or anything: how do we make that differentiation between the machine that can make its own decisions and can change its mind and the human being responsible for it?"

Maritime autonomous operations are also discussed on the level of impact on society at large. Trust is connected especially to the concept of technology acceptance by the potential users, but also by the wider public. A similar issue is the subject of a broad discussion concerning autonomous driving, public transport, and medical devices (Fraedrich & Lenz, 2016; Hulse, Xie, & Galea, 2018; Waytz, Heafner, & Epley, 2014). Technology acceptance is linked by the HUMANE participants to other issues like liability for maritime accidents and environmental concerns.

Discussion

The vision of the autonomous maritime future includes humans and RIA working together and forming dynamic relationships. Designing sociotechnical systems sustaining human RIA cooperation requires extensive reflection on the issues of operational trust, transparency, organisational trust, and social acceptance.

Operational trust is conceptualised as a continuum in which extreme values should be avoided. However, it is challenging to define what an appropriate or correct level of trust would be. A possible answer is a correspondence or equivalence between the objective capabilities of technology and the operator's representation of thereof. The optimal level of trust can be linked to the concept of calibrated trust, which is reflected by a strong correlation between the human's trust and the trustworthiness of the technology. Therefore, the goal of design and training interventions should not be to increase human trust, but to calibrate trust with RIA’s capabilities.

The mental representation of capabilities of technology could be built not only by familiarising users with the technical specifications but on providing superficial cues – how advanced and intelligent does this artefact appear to be? Technology can be perceived as more autonomous than it really is when it provides insufficient feedback to the user. Therefore, the degree to which RIA behaviour is perceived as autonomous is an important measure that should be addressed in the design process.

The relationship between humans and RIA does not happen independently of the broader context. There is evidence suggesting that organisational trust plays role of a moderator of trust in human RIA collaboration. Tackling organisational trust is already relevant for conventional operations, due to unfavourable factors specific for the maritime industry, like physical distance and frequent reorganisation of the crew.

Conclusions

The Human Autonomy Enable (HUMANE) workshops identified four meta-categories of trust issues relevant for MASS: operational trust, trustworthiness, organisational and trust understood as technology acceptance. The data-driven literature review recognised a number of trust-related concepts that apply to human RIA collaboration in the context of autonomous maritime operations. Developing and applying these trust related concepts in the maritime setting creates an opportunity to improve design and training. More research is needed to provide guidelines for such tasks as measuring perceived autonomy, exploring linguistic and cultural aspects of human RIA communication, facilitating calibration of trust with trustworthiness, building common understanding within instant teams, and promoting social acceptance of RIA in a responsible way.

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“Navigare necesse est, vivere non necesse”

CDR s.g. (ret.) Roar Espevik
Founder of Necesse

The quote is attributed to Pompey (56 BC), who used it to urge his sailors on when they refused to set sail on a stormy sea, in order to bring grain from Africa to Rome where people were starving. This is a task familiar to every naval officer: to do his or her duty to society when the situation demands it, is more crucial than own survival. The quote means, literally, “It is necessary to sail, it is not necessary to live”. This means that it is necessary to depart, even if you are not at all sure that you will ever arrive.

It is more “necesse” than ever that we set sail within the academic world. The picture on this last page, the possible monster, Nessie of Loch Ness, symbolizes our quest for knowledge within the naval domain. What is truth? With what kind of certainty can we claim to know the truth? These are central questions whether dealing with a monster or with naval warfare. It is an ongoing process that makes us wiser but not certain. The Royal Norwegian Naval Academy dates back 200 years and the purpose of our magazine is to put our competence, or sometimes even the lack of it, out into the open for debate. We have a threefold wish; to invite to debate and reflection, to present competent arguments, and to publish knowledge gained through peer reviewed research. In short, we have a deep desire to present through “Necesse” our latest academic thoughts, research and efforts concerning anything that is important to a naval officer. “Necesse” will include scientific articles, especially brilliant bachelor papers by our cadets, and works of scholars at our own Academy or others writing within the naval officer sphere.